PUBLIC ROADS

A JOURNAL OF HIGHWAY RESEARCH

UNITED STATES DEPARTMENT OF AGRICULTURE
BUREAU OF PUBLIC ROADS

VOL. 11, NO. 6 ▽ AUGUST, 1930

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FREEZING AND THAWING OF SOILS AS FACTORS IN THE DESTRUCTION OF ROAD PAVEMENTS

By STEPHEN TABER, Professor of Geology, University of South Carolina, Columbia, S. C.

Soils, when frozen under natural conditions, generally behave as open systems with respect to water. The extent of heaving may be either greater or less than that encountered when freezing occurs in a closed system. Some soils, under certain conditions, freeze with no appreciable uplift of the surface, while others give uplifts as great as 60 per cent of the depth of freezing. Soils that are very impermeable because of high colloid content behave in laboratory tests essentially as closed systems. These include certain muck and gumbo soils, and soils containing bentonite.

Laboratory experiments show that excessive heaving is always accompanied by the segregation of ice in layers or lenses. Similar segregations have been observed when excavations were made in badly heaved ground. The factors which chiefly affect ice segregation are texture of soil, composition of soil, supply of water, rate of removal of heat, and surface load.

Various measures are suggested for the elimination or reduction of damage due to ground freezing, thawing, and alternate freezing and thawing. Proper drainage is always essential. Placing a thick layer of coarse material under the pavement, extending to the extreme depth of ground freezing, is an effective but expensive method. Addition of sand to the subgrade will prevent ice segregation. Uniformity of texture in subgrade soils is essential to the avoidance of differential heaving.

Extensive research in the problems of ground freezing is recommended.

FREEZING AND THAWING have caused much damage to road pavements in cold climates, but the processes involved have not been clearly understood, and therefore some of the preventive measures adopted have proved to be of little or no value. It has been generally assumed that the uplift of the surface soil is due to the change in volume which accompanies the freezing of water, and that expansion is upward because of the less resistance in that direction. But these assumptions are founded on experiments in which water was frozen in closed systems; whereas soils when frozen under natural conditions usually behave as open systems with respect to water, and experiments with open systems lead to quite different conclusions. The freezing experiments of early investigators seem to have been limited to closed systems.

In an investigation of frost heaving begun in 1914 the author experimented with open systems. These experiments, which were carried out on cold nights, indicated that the pressure effects accompanying freezing are due to the growth of ice crystals and that excessive heaving is to be explained by the segregation of water as it freezes. This segregation was obtained in clay but not in clean sand. After the publication of brief descriptions of some of the experiments, together with the conclusions mentioned above,[1] the investigation was dropped temporarily, because of lack of facilities for obtaining and maintaining low temperatures.

The investigation was resumed in March, 1927, with an electric refrigerator, which made close control of temperature possible. Since November, 1927, the work has been carried on through the financial cooperation of the United States Bureau of Public Roads. Two papers have resulted from this research; the first[2] being primarily a description of experiments performed in order to determine the effect of different factors on the freezing of soils, while the second[3] was devoted to a discussion of the theory of frost heaving. The present paper contains a description of the apparatus and technique used in the investigation, a brief review of the more important experiments, and a discussion of the ways in which freezing and thawing of soils may affect pavements.

APPARATUS DESCRIBED

The apparatus (see fig. 1) is set up in an unheated basement room, on a cement floor several feet below ground level, so that the room temperature changes very slowly and is practically constant during the experiments, which seldom continue for periods of more than one week. The refrigerator, well insulated with cork packing, is cooled by expansion coils placed across the top of the cabinet. Sulphur dioxide is used in the cooling system, and the compressor, operated by a one-fourth horsepower motor, is placed on a separate foundation so as to eliminate all vibration. The temperature control is automatic. The temperature of the air in the cabinet is recorded by a thermograph and checked by a maximum and minimum thermometer. When tests are made under uniform conditions the temperature can be kept practically constant, except for fluctuations amounting to between 2° and 3° C., which are due to the periodic starting and stopping of the motor.

A box containing sand, placed in the bottom of the cabinet, is insulated on all sides with a packing of glass wool. The soils to be frozen are packed in containers, which are then buried to their tops in the sand, so that freezing takes place from the top down, just as in the ground.

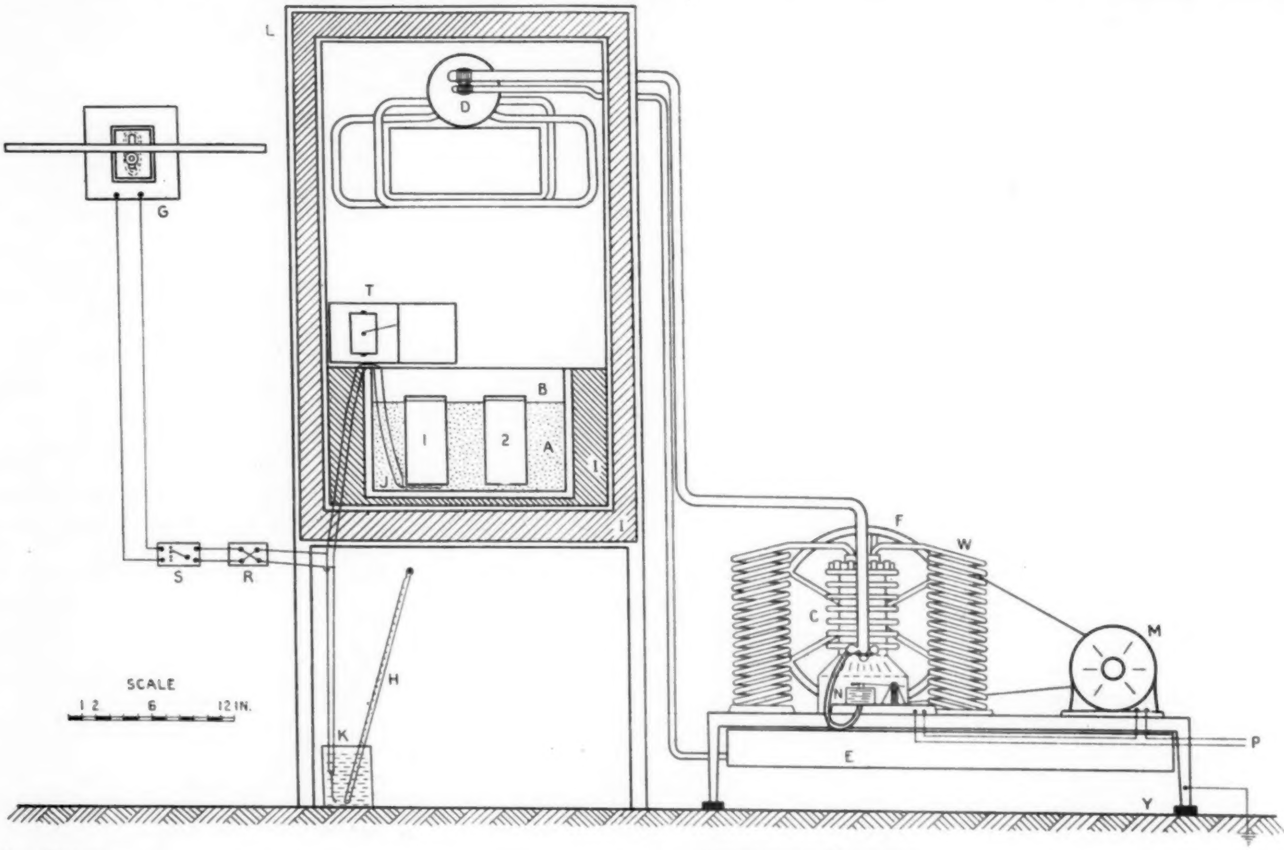
The cold junction of a thermocouple can be buried in the soil at any depth at which a record of the temperature is desired; the warm junction being kept in water containing a Beckman thermometer graduated to hundredths of a degree centigrade. Readings are made on a D'Arsonval reflecting galvanometer. The alternating current operating the motor has no effect on the galvanometer readings; but it is necessary to ground the compressor frame, as otherwise a static charge is set up by the compressor belt which makes accurate readings impossible. The temperature of the soil a short distance below the surface is unaffected by the slight variations in the temperature of the air due to intermittent operation of the compressor, and cooling follows a smooth curve. (See fig. 2.)

In most tests the soils have been frozen in cylindrical pasteboard containers, saturated with paraffin. At the close of the experiment the container is quickly cut away from the frozen soil cylinders, which may then be examined, measured, and photographed. At first gallon-sized containers were used, but later most of the tests were made with standard quart cartons, 16 centimeters in height and 8.5 centimeters in diameter,

[1] "The Growth of Crystals Under External Pressure," Amer. Jour. of Sci., Vol. XLI (1916), pp. 544-545; "Ice Forming in Clay Soils Will Lift Surface Weights," Eng. News-Record, Vol. LXXX (1918), pp. 262-263; "Surface Heaving Caused by Segregation of Water Forming Ice Crystals," *ibid.*, Vol. LXXXI (1918), pp. 683-684.

[2] "Frost Heaving," Jour. of Geol., Vol. XXXVII (1929), pp. 428-461.

[3] "The Mechanics of Frost Heaving," Jour. of Geol., Vol. XXXVIII (1930), pp. 303-317.



A—SAND
B—FREEZING BOX
C—COMPRESSOR
D—EXPANSION DRUM AND COILS
E—SO_2 RESERVOIR
F—FLYWHEEL AND FAN
G—GALVANOMETER
H—BECKMAN THERMOMETER
I—INSULATING PACKING
J—COLD JUNCTION OF THERMOCOUPLE
K—WARM JUNCTION OF THERMOCOUPLE
L—FREEZING CABINET
M—MOTOR
N—TEMPERATURE CONTROL
P—SOURCE OF POWER
R—REVERSIBLE SWITCH
S—SHUNT BOX
T—THERMOGRAPH
W—CONDENSING COILS
Y—RUBBER SHOE
1, 2—TEST SPECIMENS

FIGURE 1.—APPARATUS USED IN FREEZING SOILS

as satisfactory results were obtained with them and a larger number of simultaneous tests could be run than with the larger containers. In experiments where it was desired to reduce friction between frozen soil and container, a lining of celluloid or of heavy greased paper was inserted. The cartons were strengthened when necessary by winding with tape saturated with shellac. The strongest containers used were made from heavy fiber cylinders 9 centimeters in diameter, having walls 7 millimeters thick. They were made impervious with paraffin or shellac, and, in tests conducted under the highest pressures, they were surrounded with wood strips, held in place by steel bands. Metal containers are unsatisfactory because of their rapid conduction of heat. It is also desirable that the containers be opened quickly before melting occurs.

In some tests it is necessary to maintain the water content of the unfrozen soil in the lower part of the carton, replacing it as fast as it is withdrawn because of freezing above, thus simulating the way in which water may be fed up from the water table during the freezing of soils in the ground. To accomplish this, small holes are punched in the bottom of the carton and covered with filter paper before introducing the soil. The carton is then placed in a vessel containing about one-half inch of coarse sand, saturated with water. In saturating the side walls of the containers with paraffin, care must be taken to keep the bottom free of paraffin, otherwise water will not readily enter through the small holes. A collar, fitting snugly around the carton and resting on the top of the vessel, prevents entrance of the dry sand in which the apparatus is packed. The water level in the saturated sand is maintained by adding water through a rubber tube, which passes through the packing to the outside. The pressures exerted during freezing are measured by observing the compression of a heavy steel spring which has previously been calibrated.

Simple apparatus for recording the amount and rate of surface uplift during the freezing of water in an open system is shown in Figure 3. A thick-walled container, filled with the soil to be tested, stands in a vessel containing sand, which is kept saturated with water. It is held rigidly in place by a strong frame. A heavy lead disk resting on the soil in the container carries a pen which traces a continuous record on the

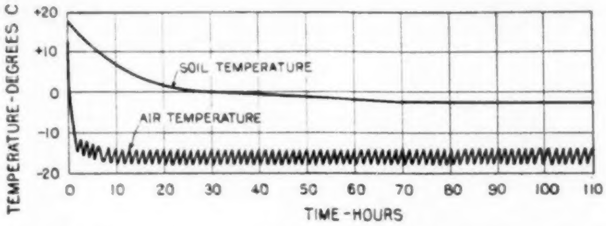
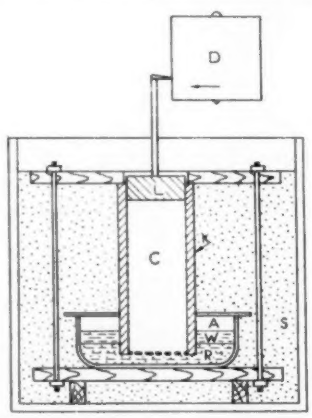


FIGURE 2.—GRAPHS SHOWING THE AIR TEMPERATURE IN THE REFRIGERATOR AND THE SOIL TEMPERATURE 12 CENTIMETERS BELOW THE SURFACE DURING A FREEZING EXPERIMENT

revolving drum of a thermograph. As freezing gradually penetrates downward from the surface, the interstitial spaces in the soil below the zone of freezing furnish passages through which the water can move either upward or downward according to the forces to which it may be subjected, for it can easily enter or leave the container through the perforations in the bottom.



L—LEAD DISK WITH RECORDING PEN
R—SAND SATURATED WITH WATER
D—DRUM TURNED BY A CLOCK
K—CONTAINER
S—DRY SAND
W—WATER
C—SOIL
A—AIR

FIGURE 3.—APPARATUS FOR FREEZING SOILS IN A SYSTEM THAT IS OPEN WITH RESPECT TO WATER. THE AMOUNT OF HEAVING IS RECORDED ON A ROTATING DRUM

FREEZING PRODUCES DIFFERENT EFFECTS IN CLOSED AND IN OPEN SYSTEMS

When water is cooled under atmospheric pressure it normally freezes at 0° C. or a little below, with an expansion in volume of about 9 per cent. Increase in pressure, so long as it does not exceed 2,115 kilograms per square centimeter, lowers the freezing point. If water is frozen in a confined space, the pressure developed depends upon the resistance that is offered to expansion, but there is a limit to the pressure that can be obtained. The maximum pressure obtainable through the freezing of water in a closed space is, according to Bridgman, 2,115 kilograms per square centimeter; for at this pressure and − 22° C. ice III, which is denser than water, begins to form.[4] Tammann[5] obtained a slightly higher figure but the difference is not great. In a closed system, freezing results in pressure because the water is so confined that it can not escape, and the amount of heave varies directly with the quantity of water frozen.

In experiments performed with the apparatus shown in Figure 3 on soil systems that are open with respect to water it was found that soils differ greatly in the amount and rate of heaving, and that even the same soil will behave differently under different conditions of freezing. Some soils, under the most favorable conditions and when saturated with water, freeze with no appreciable uplift of the surface, while others give uplifts ranging up to more than 60 per cent of the depth of freezing. An uplift of even 100 per cent may be obtained through the formation of a layer of ice at the surface when the soil is too warm to permit freezing within the soil voids. When no heaving occurs, or when the heaving is less than that which results from the expansion in volume of the water frozen, it is obvious that some of the water must be pushed downward through the soil voids by the growing ice crystals and expelled from the soil container. On the other hand, when the surface uplift exceeds that which may be attributed to change in volume, additional water must enter the container as a result of the freezing.

SOILS OUT OF DOORS GENERALLY BEHAVE AS OPEN SYSTEMS

Observations out of doors show that most soils when subjected to freezing under natural conditions usually behave as open systems rather than as closed systems. In some places frost heaving is too great to be explained by the expansion in volume of water present in voids and in other places it is too little.

The average soil seldom contains as much as 50 per cent water, but if all the water in such a soil were to freeze in situ the change in volume could cause an uplift of less than 5 per cent of the depth of freezing. Moreover, in most soils having a high water content a considerable percentage of the water does not freeze. The depth of freezing in the colder parts of the United States seldom exceeds 2 or 3 feet; yet a surface heaving of 6 inches is not uncommon and an uplift of "a couple of feet" has been reported. The maximum amount of frost heaving that occurs during cold winters is not known, as very few accurate records are available, most observers having measured the difference in uplift of points located close together rather than the amount of uplift with reference to a bench mark that has not been disturbed by frost.

Although frost heaving at some points is excessive, at others the freezing of soils may be accompanied by no appreciable uplift. Frequently there is great difference in the amount of heaving within relatively short distances. Along a paved highway in New Hampshire the differential heaving was as much as 6 inches within a distance of 50 feet.

In laboratory experiments excessive heaving is always accompanied by the segregation of some of the water to form layers or lenses of more or less pure ice (see figs. 14, 17, and 18); and similar layers of segregated ice have been found when excavations have been made in badly heaved ground. The lump of clay containing thick ice layers, shown in Figure 4, was obtained in the spring of 1929 by Mr. F. C. Lang, of the Minnesota Department

[4] P. W. Bridgman, Proc. Amer. Acad., Vol. XLVII 1912), pp. 441–558.
[5] Gustav Tammann, "The States of Aggregation," translated by R. F. Mehl, New York (1925), pp. 158–175.

of Highways, under a street in St. Peter, Minn., where the amount of heaving was said to be a "couple of feet." It is obvious that ice layers are not formed in soil by the freezing of water in situ.

The local segregation of water in soil to give excessive frost heaving is usually compensated for, under natural conditions, by the expansion of air imprisoned in the soil or by the entrance of additional air through pores and cracks. The partial expulsion of water from soil voids in an area where freezing results in little or no heaving is usually compensated for by the compression or expulsion of air either locally or under adjacent areas.

FIGURE 4.—CLAY CONTAINING ICE LAYERS FROM UNDER A BADLY HEAVED STREET IN ST. PETER, MINN.

FEW SOILS BEHAVE AS CLOSED SYSTEMS

Probably few soils freezing naturally out of doors behave as absolutely closed systems with respect to water, for in order for this to occur the resistance to the movement of ground water has to be very high. In laboratory tests, soils that are very impermeable because of high colloid content behave essentially as closed systems, the amount of heaving being the same whether the containers are sealed at the bottom or whether they are perforated and stand in water. The surface uplift in both cases is equal to the change in volume of the water frozen. This subject is discussed under the heading "Tests made with soils containing bentonite." (See fig. 12, B.) Segregated ice forms in such soils when the water content is sufficiently high, but the ice crystals are built up of water drawn from the immediately adjacent soil. The only soils thus far tested that behave on freezing like closed systems, because of impermeability, are certain muck and gumbo soils, and soils containing bentonite.

If water begins to freeze simultaneously over a large area where air is excluded from the soil, the resistance to the movement of ground water may be so great as to give the effect of a closed system. Such conditions obtain where the water table is absolutely parallel to the surface and there is no local variation in soil or soil cover. These requirements practically limit closed soil systems to swampy areas; but even there, if the soil texture is favorable, lenses and layers of segregated ice may form. The uplift, however, will not exceed the volume change of the water frozen, except as voids formerly occupied by water become filled with air.

There is a gradation, and not a sharp demarcation, in the conditions that cause soils to freeze as open rather than as closed systems, and the conditions may change even during the freezing of soil. For example, when a sandy soil saturated with water begins to freeze it may behave practically as a closed system, the uplift equaling the change in volume of the water frozen; but as freezing progresses the weight of the frozen crust that must be lifted increases until the volume change is adjusted in part by forcing water out of soil voids immediately below; and finally, when the weight of the crust is sufficiently great, adjustment may be brought about almost entirely in this way, so that there is no uplift.

As resistance to the movement of ground water in soils increases an open system tends to grade into a closed system. Each individual area is a problem in itself, and it will take much field work as well as laboratory study to determine the relative importance of the different factors that determine whether a soil on freezing will behave as a closed or as an open system.

FIGURE 5.—TEST TUBE CONTAINING FROZEN CLAY. LAYERS OF SEGREGATED ICE IN THE UPPER PART OF THE TUBE WITH SHRINKAGE CRACKS BELOW

DIRECTION OF GROWTH OF ICE CRYSTALS AN IMPORTANT FACTOR

The pressures resulting from freezing are due to the growth of crystals. A crystal can develop pressure only in those directions in which it is growing. If the growing crystal exerts pressure against a liquid that is confined, hydrostatic pressure is the result; but in a closed system the crystal is able to exert pressure only if crystallization is accompanied by an increase in volume.

In open systems, where the liquid can escape, the pressures resulting from freezing are not hydrostatic, but are due directly to crystal growth, and are effective only in the direction of growth. Liquids such as benzene and nitrobenzene, that solidify with decrease in volume, give a pressure effect similar to that of water when substituted for it in freezing experiments with open systems, though they are incapable of developing pressure when frozen in closed systems.

An ice crystal grows in those directions in which it is in contact with undercooled water; or, stated in a different way, the growth of an ice crystal in any particular direction is determined by three factors: (1) The presence or absence of water in contact with the crystal in that direction, (2) the temperature at the contact,

and (3) the pressure at the contact. In most cases where water freezes as a result of natural processes, heat is conducted away from the growing ice crystals in one direction and they are in contact with water only in the opposite direction; therefore growth takes place in a single direction. This is the way water freezes in lakes. The factors that control the direction of crystal growth are illustrated in the experiments described below.

It is difficult to break thin glass test tubes by freezing clear water in them if they are uniform in bore and open at the top, even though they be exposed to cooling from the side instead of from the top, because water expands on cooling from 4° to 0° C., and therefore the coldest water tends to rise and come in contact with the downward growing crystals. If the tubes are sealed, or if there are irregularities in the bore, hydrostatic pressure develops and rupture occurs at the weakest place. Sand placed in the water will prevent convection currents, but the test tubes are not usually ruptured on freezing, for the crystals stop growing horizontally when they come in contact with a solid.

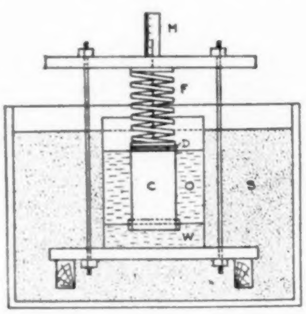


FIGURE 6.—APPARATUS FOR FREEZING CLAY CYLINDERS UNDER HEAVY VERTICAL PRESSURE WITH NO LATERAL SUPPORT

If clay or some other very fine material is introduced in the water, convection currents are prevented, but, what is more important, water is able to reach the surfaces of growing ice crystals through the interstitial capillary spaces. This is due to the fact that water does not readily freeze in very small capillaries.[6] Test tubes containing clay and water, when exposed to cooling from the sides, are broken, for the ice crystals grow radially inward and exert pressure against the walls of the tubes. Similar tubes, buried in dry sand so that cooling is from the top down, are not broken, for the crystals grow in a vertical direction. Alternating layers of clear ice and frozen clay are formed near the top of the tubes, while shrinkage cracks develop in the clay below as water is withdrawn to build the ice layers above. The test tube shown in Figure 5 was slightly cracked, accidentally, before it was buried in sand. On freezing, the cracks extended around the test tube and the fragments were separated in a vertical direction, but no longitudinal cracks appeared, for the crystals did not grow from the wall inward.

Similar freezing tests have been made on open systems where it was possible for water to enter or be expelled. A cylinder 6 centimeters in diameter, cut

FIGURE 7.—CLAY CYLINDER FROZEN UNDER HEAVY VERTICAL PRESSURE WITH NO LATERAL SUPPORT

from somewhat indurated clay, was placed in a small tray with perforated bottom, and moist clay tamped around it to hold it in place, a strip of adhesive tape having been wrapped around the bottom of the cylinder to help prevent slaking because of rapid absorption of water. The tray was embedded in a layer of sand saturated with water contained in a large carton (see fig. 6), and then oil was poured in until level with the top of the clay. This oil is sufficiently viscous when cold to eliminate convection currents, while it does not solidify at low temperatures. A steel disk placed on the clay cylinder supported a stiff spring which could be compressed against a plate held in place by bolts. The vertical pressure and the amount of heaving were shown on a scale by the position of an indicator that extended from the clay up through the spring. The apparatus was buried in dry sand so that freezing was from the top down.

In one test the bolts were tightened to give an initial pressure of 101 pounds before cooling was started. Five hours later the pressure had dropped to 94 pounds because of slow failure of the cylinder, but after 15 hours heaving had restored the initial pressure, and at the end of 76 hours, when freezing had reached the bottom, the pressure was 140 pounds (2.3 tons per square foot). The heaving was due to the formation of horizontal layers of fibrous ice ranging up to 0.5 centimeter in thickness. (See fig. 7.) The cracks, due to failure of the cylinder under pressure, contained almost no ice, being filled chiefly with oil. In this test heaving was upward in spite of heavy vertical pressure and practically no lateral resistance. In tests conducted under less initial pressure, failure of the clay cylinders did not occur, and their appear-

[6] Stephen Taber, "The Growth of Crystals Under External Pressure," Am. Jour. Sci., Vol. XLI (1916), pp. 544-545, 552.

ance after freezing was similar to that of the cylinders shown in Figures 17 and 18. The pressure developed in this experiment was limited by the crushing strength of the clay cylinder.

In another experiment clay was packed around copper bars in a carton with perforated bottom which stood in sand kept saturated with water. The apparatus was then buried in dry sand and subjected to

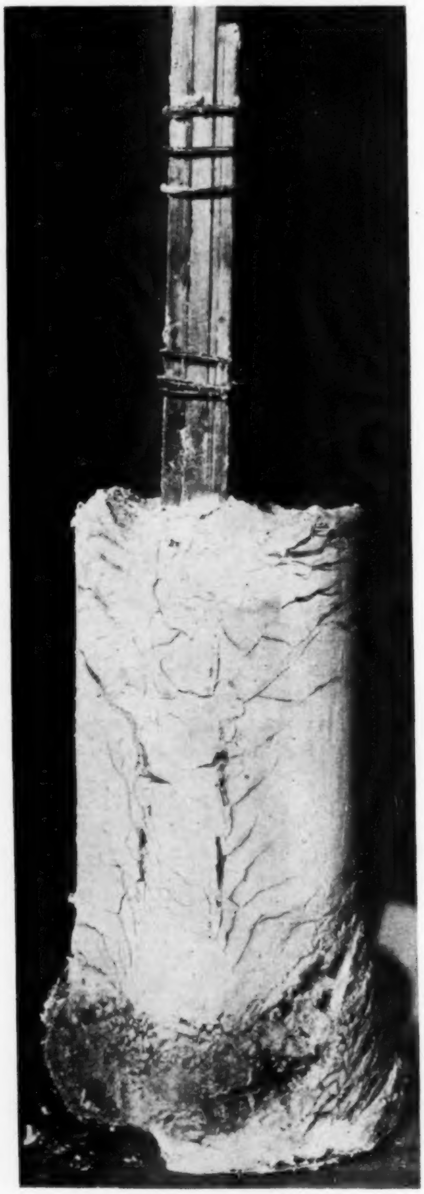


FIGURE 8.—CLAY CYLINDER ENLARGED BY GROWTH OF ICE CRYSTALS OUTWARD FROM COPPER BARS

freezing temperatures. Resistance was least in a vertical direction, but rapid conduction of heat by the copper caused ice crystals to grow outward from its surface (see fig. 8), and the carton was ruptured near the bottom.

Wet clay was packed in wrought-iron cylinders having a bursting strength of over 11,000 pounds per square inch, the ends being sealed with wooden plugs. On its being subjected to freezing temperatures, ice crystals grew radially inward at first, forming a layer of ice in contact with the metal, but as the pressure increased the end plugs were slowly driven out by the growth of ice crystals in the direction of least resistance. These crystals built up ice layers transverse to the axis of the cylinder. The ice crystals grew in the direction of least resistance, although heat conduction was most rapid in a transverse direction. However, the difference in temperature in different directions must have been small. Ice crystals will continue to grow in those directions in which they are in contact with water, if the temperature at the ice-water surface is below the freezing point for the existing pressure. With any increase in pressure the temperature must be lowered if crystal growth is to continue, but a pressure of 145 kilograms per square centimeter is required to lower the freezing point from 0° to −1° C. Effects that may be attributed to difference in pressure or difference in the resistance to crystal growth are rarely observed where soils freeze under natural conditions; and the direction of heaving is, therefore, usually determined by the direction of heat conduction and the availability of water.

VARIOUS FACTORS DETERMINE ICE SEGREGATION IN SOILS

The physical laws that control the freezing of water are the same in the laboratory as out of doors, but in the laboratory it is possible to vary one factor at a time while the others are kept constant, a method that is not usually possible under natural conditions. This is especially true of the factors that control ice segregation in soils; and these factors are of major importance, since they determine the amount of heaving in open systems. The effects of different factors on the freezing of water in soils were described in the paper on Frost Heaving, from which the following account is in part abstracted. Subsequent study has disclosed some additional facts which are included.

TEXTURE OF SOILS AFFECTS ICE SEGREGATION

Texture, as applied to soils, refers to the size, shape, and arrangement of the individual particles, the degree of consolidation, and, largely determined by the foregoing, the size and percentage of voids.

Size of soil particles is one of the most important factors controlling segregation of water during freezing. As the maximum size permitting segregation varies with the other factors, it is essential that all tests be carried through under exactly the same conditions if comparable results are to be obtained.

Quartz ground to pass a 200-mesh sieve (maximum particle diameter about 0.07 millimeter) showed faint segregation near the surface under favorable conditions of cooling and no surface load. (See fig. 9, A.) The material was packed in a carton which was buried to the top in dry sand while the bottom was kept saturated with water. The initial temperature was 20° C. The air temperature at the surface was then rapidly lowered to −15° C. (see fig. 2.) and maintained with a variation of only about 3° until the close of the test. There was no surface load, but as freezing progressed downward the weight of material that had to be lifted gradually increased as did likewise the friction of the frozen soil against the walls of the carton. Quartz dust having an average particle diameter of between 6 and 10 microns gave slightly greater evi-

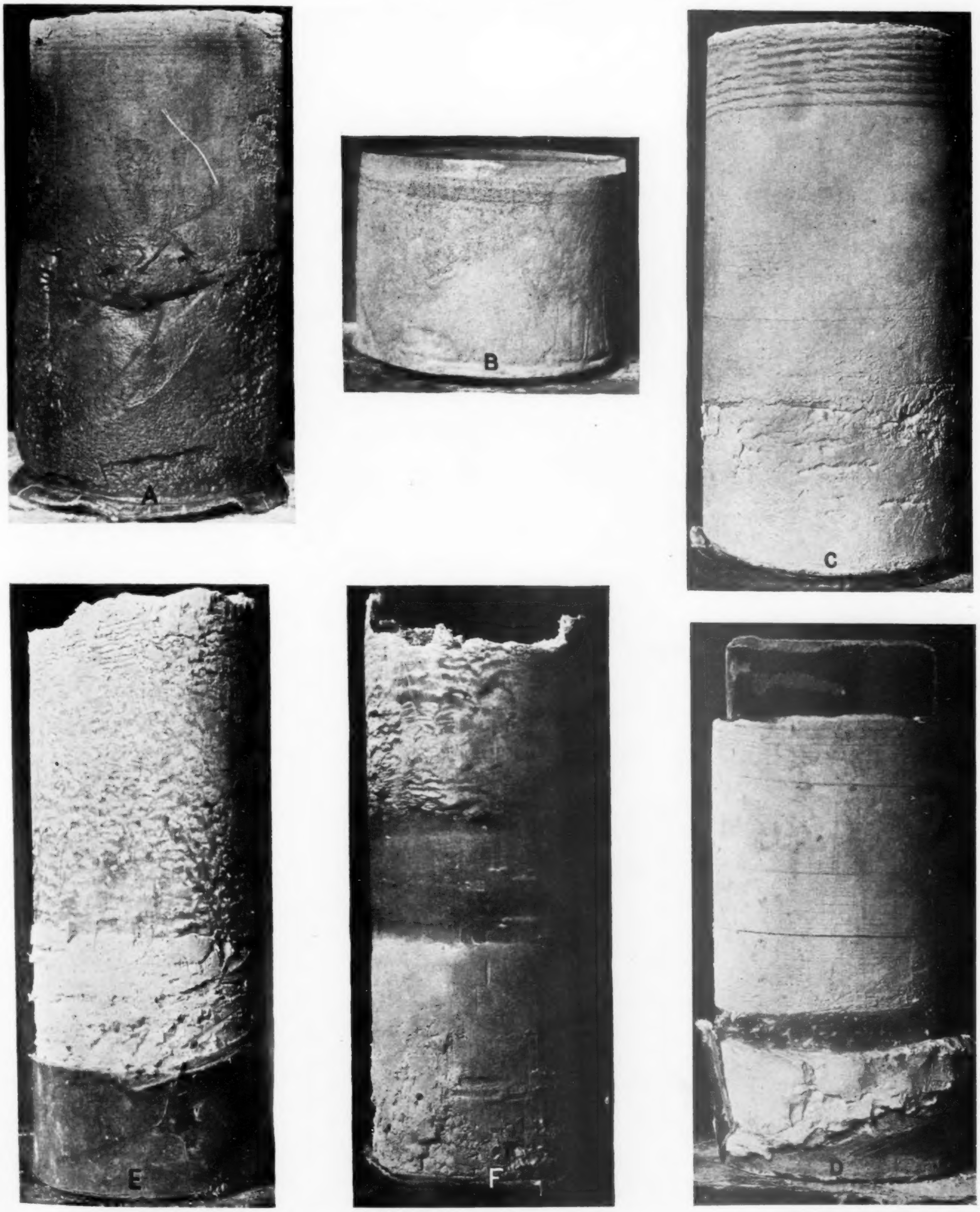


Figure 9.—Specimens Showing Influence of Soil Texture on Formation of Segregated Ice: A—Quartz Flour, Maximum Particle Size About 0.07 Millimeter, Showing Slight Banding near Top Due to Ice Segregation. B—Quartz Flour, Particle Size 6 to 10 Microns. Slight Banding Due to Ice Segregation. C—Barium Sulphate, Particle Size About 2 Microns, Showing Segregation of Ice. D—Barium Sulphate with Ice Layer at Lower Limit of Freezing; Thin Ice Layers Above. Iron Weight on Top. E—Lithopone, Particle Size One-half Micron, Showing Segregated Ice. F—Kadox, Particle Size One-fourth Micron, with Layer of Pure Ice 5 Centimeters in Thickness.

dence of segregation when tested in the same way. (See fig. 9, B.)

In some of the tests chemically precipitated crystals of various substances were substituted for quartz in order to obtain greater uniformity in particle size. Barium sulphate, having an average particle diameter of about 2 microns and a maximum diameter of only 3 microns, gave well-defined segregation when tested in the manner described above (see figs. 9, C and 9, D), but under a surface load of 30 pounds per square inch no heaving occurred; and, also, when the material as a whole was brought to a temperature of 0° C., before freezing rapidly from the top down, no segregation took place.

Segregated ice forms easily in materials with a particle size of 1 micron or less. Results obtained with lithopone, having a particle diameter of about one-half micron, and with kadox, which has a probable particle size of one-fourth micron or less, are shown in Figures 9, E and 9, F. The clay used in most of the tests is a very pure South Carolina Cretaceous white clay, which consists largely of particles having apparent diameters of between one-half and one micron; but it is very difficult to distinguish the ultimate particles from aggregates. Part of the material is much finer.

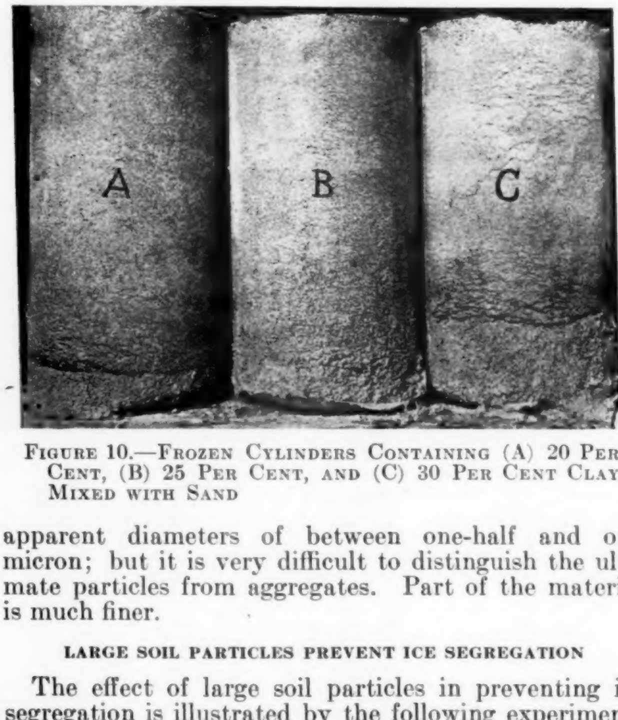


FIGURE 10.—FROZEN CYLINDERS CONTAINING (A) 20 PER CENT, (B) 25 PER CENT, AND (C) 30 PER CENT CLAY MIXED WITH SAND

LARGE SOIL PARTICLES PREVENT ICE SEGREGATION

The effect of large soil particles in preventing ice segregation is illustrated by the following experiments with mixtures of pure clay and standard Ottawa sand. This sand is very uniform, the grains having an average diameter of about 0.7 millimeter. Mixtures containing slightly less than 20 per cent clay by weight would have just enough clay to fill the voids between the sand grains so that the size of the pore spaces would be the same as in pure clay. On freezing no segregated ice could be observed in mixtures containing less than 30 per cent clay, and even with 50 per cent clay the amount of segregation is small as compared with tests made on pure clay. The results obtained by freezing sand-clay mixtures are shown in Figures 10 and 11.

Under more favorable conditions than those prevailing in the tests described above, segregated ice will form in soils having a somewhat larger particle size, whether the soils be of uniform grain size or contain appreciable amounts of coarser particles. In these laboratory tests freezing progresses more rapidly near the beginning than it usually does under natural conditions, and, after freezing has penetrated downward far enough to slow up the process, heaving is resisted by friction between frozen soil and container. The effects of rapid freezing and of resistance to heaving in preventing the formation of segregated ice are discussed later in this paper.

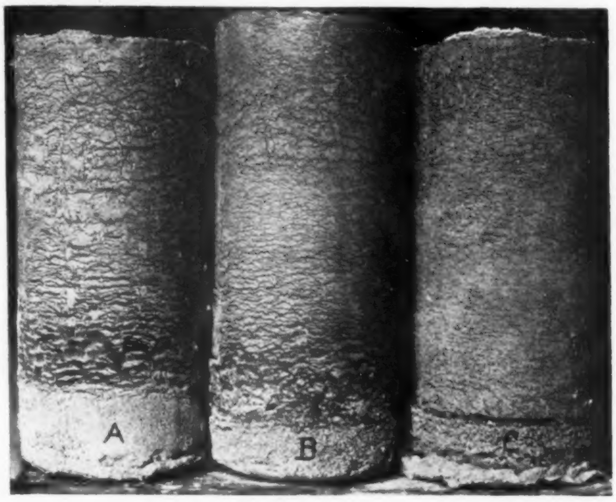


FIGURE 11.—FROZEN CYLINDERS CONTAINING (A) 50 PER CENT, (B) 40 PER CENT, AND (C) 30 PER CENT CLAY MIXED WITH SAND

TESTS MADE WITH SOILS CONTAINING BENTONITE

Experiments were also conducted on soils containing different percentages of colloidal material. Colloidal particles are supposed to range in size from about 0.1 to 0.001 of a micron, but the size of particle in the colloidal materials used is not known. Most of the tests were made on bentonite and mixtures of bentonite with the South Carolina Cretaceous white clay. The bentonite used consists chiefly of minute micaceous crystals of montmorillonite or beidellite, which separate into flakes of colloidal thickness, while the Cretaceous clay is, for a clay, relatively low in colloidal material.

When mixed with water, bentonite expands to several times its original volume, and when wet it becomes very impermeable. Cartons packed with dry bentonite and stood in wet sand are ruptured by the change in volume. When packed in a strong glass container having a perforated bottom, water was absorbed rapidly through the bottom until a thin layer of bentonite became saturated, then the entrance of water became extremely slow, and at the end of nine months it had penetrated to a height of only 4 centimeters, even though the water was kept under a head of 30 centimeters. It was therefore necessary in freezing tests to mix the bentonite thoroughly with water before placing it in cartons.

Mixed with water bentonite forms a jellylike mass, which is so impermeable that water can be drawn only a short distance to build segregated ice. On freezing from the top downward, tension is set up in the bentonite immediately below a growing ice layer. Since the stress is uniformly distributed and the material homogeneous, vertical cracks tend to develop, which in horizontal sections form a polygonal pattern. (See

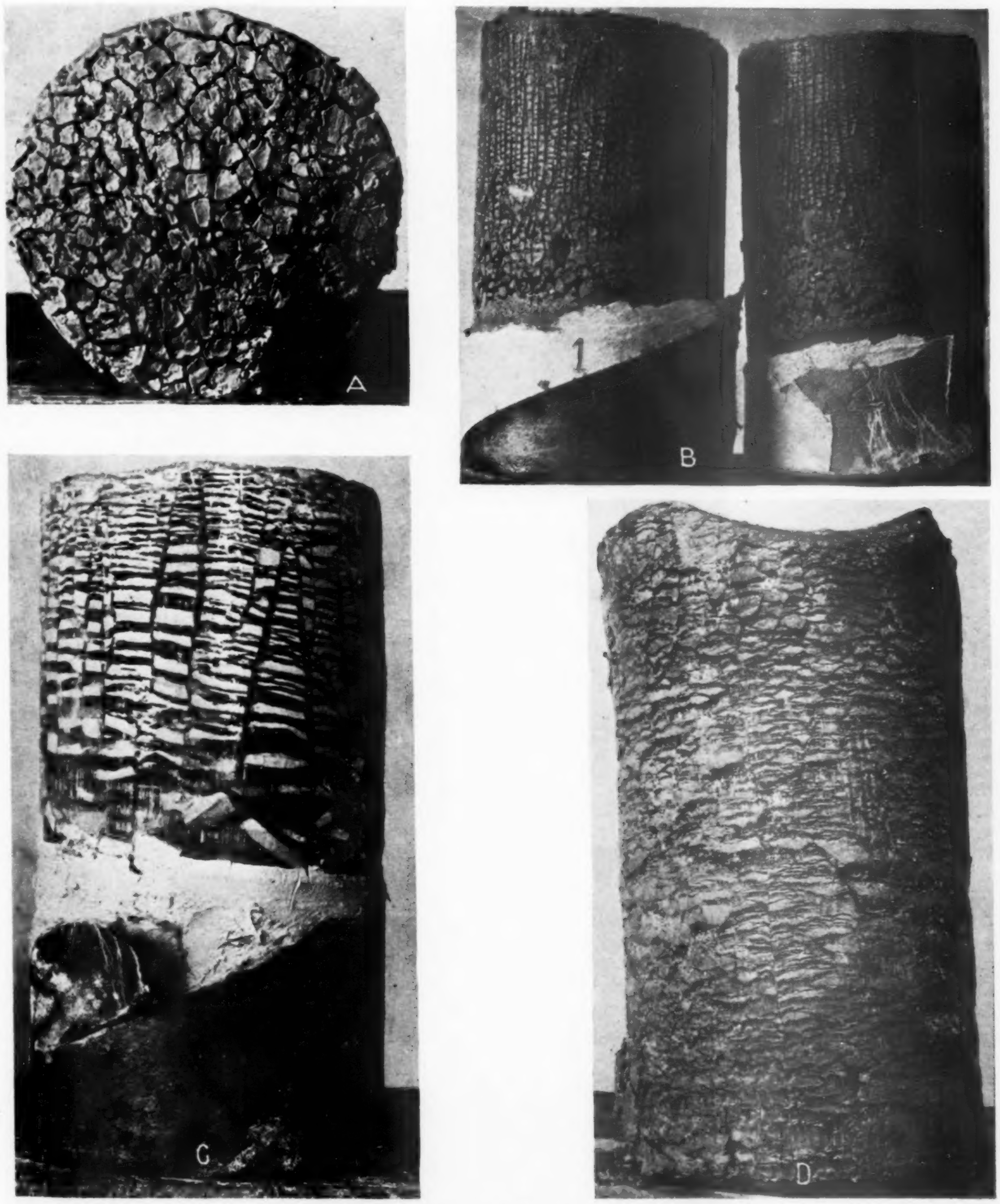


FIGURE 12.—RESULTS OF FREEZING TESTS MADE ON SPECIMENS CONTAINING BENTONITE. A.—POLYGONAL PATTERN FORMED ON FREEZING A MIXTURE CONTAINING 25 PER CENT BENTONITE AND 75 PER CENT CLAY. B.—CELLULAR STRUCTURE FORMED ON FREEZING A MIXTURE OF BENTONITE AND WATER. CARTON NO. 1 STOOD IN WATER. CARTON NO. 2 WAS SEALED AT THE BOTTOM. C.—CELLULAR STRUCTURE FORMED ON FREEZING 94 PER CENT CLAY AND 6 PER CENT BENTONITE MIXED WITH WATER. D.—THE RESULT OF FREEZING 4 PER CENT BENTONITE MIXED WITH 96 PER CENT CLAY WHILE STANDING IN WET SAND

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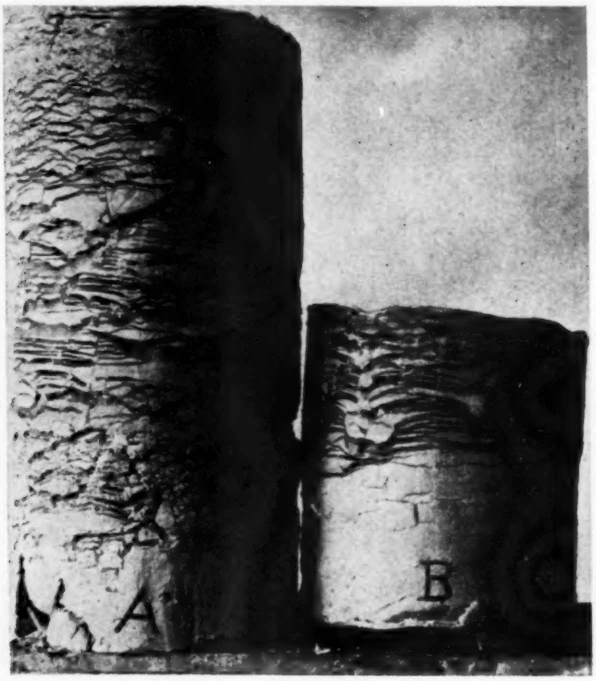


	Clay columns	
	A	B
Diameter of clay column..........centimeters..	8.5	8.5
Height of surface above water table..........do....	20.1	5.5
Height of clay column before freezing..........do....	23.5	7.7
Height of clay column after freezing..........do....	29.9	9.5
Amount of uplift..........do....	6.4	1.8
Time in freezing box..........days..	5	5

FIGURE 13.—CLAY CYLINDERS FROZEN WITH LOW WATER TABLE (A) AND HIGH WATER TABLE (B). LOWER HALF OF A REMOVED

fig. 12, A.) The cracks are gradually filled with clear ice, and as freezing progresses they advance downward, forming a columnar structure, which, combined with the normal horizontal ice layers, results in the peculiar cellular structure shown in Figures 12, B and 12, C.

The results of freezing pure bentonite mixed with 83 per cent water are shown in Figure 12, B. Carton No. 1 stood in sand saturated with water, while carton No. 2 was sealed at the bottom. No water entered the impervious mixture in carton No. 1, for the weight did not change appreciably during the experiment. Mixing clay with the bentonite so as to decrease the amount of colloids causes the polygonal cracks to become more widely spaced. Figure 12, C shows the result of freezing a mixture containing 6 per cent bentonite and 94 per cent clay in a carton that was closed at the bottom.

A dry mixture of clay with 4 per cent bentonite was sufficiently permeable so that, when the container was placed in saturated sand, water was slowly absorbed. The result of freezing this mixture as an open system is shown in Figure 12, D.

Tests were run on several natural soils which in open systems gave little or no heaving beyond that due to change in volume of water frozen. These soils contained a relatively high percentage of colloids, for they swelled greatly on absorbing water, and were so impermeable that water could not rise in the dry material higher than 10 or 15 centimeters in a period of a week. Some of these soils were clays of the gumbo type and others were muck soils containing much partly decomposed vegetable matter.

The clay minerals occur chiefly in the form of flat tabular particles, which therefore have a larger surface than particles of the same volume that are more nearly spheroidal. Also, when the particles are given parallel orientation the voids are smaller in diameter than in soils made up of irregular or spheroidal particles having the same volume.

The size of the capillary spaces in soils determines the height to which water may be lifted above the water table by surface tension, the height varying inversely as the diameter of the capillaries. In very fine soils water may rise 3 meters or more, but most fine soils contain colloids which decrease permeability and retard the movement of water.

During the growth of an ice layer in soil, water is not supplied by capillarity, for there is no free surface or meniscus. The force causing the upward flow of water to feed growing ice crystals is greater than that which results in the capillary rise of water in soil. This fact is illustrated in the following experiment.

Powdered clay was tightly packed in two cartons, of equal diameter but different height, which stood in sand saturated with water. The clay in the short carton became saturated with water in about 24 hours, but seven days passed before the clay in the tall carton became slightly moist on top although it was subjected to frequent tamping.

On freezing, however, water was drawn up to form ice layers in the tall carton almost as easily as in the short one. (See fig. 13.) Before making the photograph the lower half of the tall clay column was removed. The vessel in which the tall carton stood contained the most water, but in both cases all of the available water was withdrawn to form ice layers; and shrinkage cracks developed in the lower half of the tall clay column.

A thin layer of coarse sand will prevent the upward movement of water during freezing experiments. This action is probably due to interruption of the water supply by the accumulation of air in the large voids in sand.

Water occupying very small voids in soil does not freeze readily and may be undercooled in the immediate vicinity of ice crystals. When a cylinder of partly frozen clay, such as is shown in Figure 14, A, is tested with the point of a knife, the clay between the lowest ice layers is found to be soft as compared with that higher up, the hardness increasing toward the top, where the temperature was lower and freezing had gone on for a longer time.

At a given depth ice probably forms in the larger voids of clay first, and then, freezing gradually, extends to the smaller voids; but careful tests with a specially devised dilatometer show that part of the water does not freeze on prolonged exposure to low temperature. In the Cretaceous white clay 6 grams of water per 100 grams of dry clay do not freeze. Similar results were obtained with large fragments of porous porcelain saturated with water, thus proving that pore space, or the amount of surface exposed, is the essential factor rather than size of particle. In coarse sand or other material having a relative small area of surface all of the water appears to freeze. The water remaining

unfrozen in fine soils is probably adsorbed water, for adsorption is a surface phenomenon.

The degree of consolidation is an important factor in determining the amount and rate of heaving of soils. A cylinder of undisturbed Cretaceous clay will heave at the rate of 0.15 millimeter per hour, while the same clay when pulverized and tightly packed will heave 0.8 millimeter per hour. The difference in the amount of segregated ice formed is clearly shown in the photographs. (See figs. 14, A and 14, B.) The cylinder of undisturbed clay was frozen to a greater depth, for it remained in the refrigerator for seven days, while the pulverized clay heaved so rapidly that it came in contact with the support of the recording drum and had to be removed after only four days. Otherwise, both tests were frozen under the same conditions.

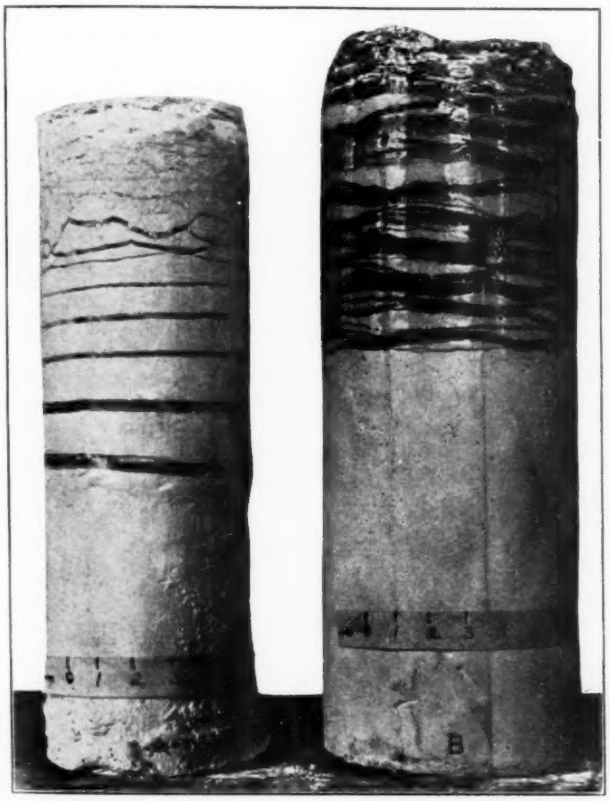


FIGURE 14.—TESTS SHOWING INFLUENCE OF DEGREE OF CONSOLIDATION ON THE AMOUNT AND RATE OF HEAVING OF SOILS. A.—CYLINDER CUT FROM UNDISTURBED CRETACEOUS CLAY AND FROZEN WHILE STANDING IN WET SAND. THE SURFACE UPLIFT EQUALS THE TOTAL THICKNESS OF THE ICE LAYERS. B.—PULVERIZED CLAY, TIGHTLY PACKED AND FROZEN WHILE STANDING IN WET SAND

The difference in the behavior of partly compacted and thoroughly compacted clay is due to several causes. The most important is probably difference in permeability. In consolidated clay some of the particles are probably in such close aggregation that they conduct heat as though the clay were partly composed of larger particles. Also, the tensile strength of the undisturbed clay is much higher.

COMPOSITION OF SOILS AN IMPORTANT FACTOR

The most abundant minerals in soils are quartz, feldspar, and the kaolin minerals. Quartz and feldspar occur as irregular grains; the kaolin minerals are usually much smaller in particle size, and some of them, with micaceous cleavage, separate readily into flakes of colloidal thickness. Humus is rarely an important constituent of subgrade soils, but locally it may make up the bulk of a soil. Colloids left by the decay of organic matter, as well as mineral colloids, decrease the permeability of soils.

The thermal properties of a soil depend upon the conductivities and specific heats of the constituents. Because of lower conductivity and higher specific heat humus changes temperature more slowly than minerals. The soil minerals differ little from one another in their thermal properties but they differ greatly from water. Since minerals cool more rapidly than water, mineral particles, and especially large ones, favor the downward movement of the freezing isotherm in soils, and therefore tend to check the growth of layers of segregated ice.

Other things being equal, soils with a high percentage of organic material might be expected to favor ice segregation, but from the tests so far made the difference appears to be slight. Most of the soils of this type so far tested are muck soils containing a high percentage of clay and so much colloidal material as to make them very impervious.

WATER SUPPLY INFLUENCES ICE SEGREGATION

When soil freezes as a closed system the only water available is the interstitial water in the zone of freezing; therefore the amount of heaving is determined by the change in volume of this water. When soil freezes as an open system and segregated ice forms, additional water may be drawn up from the water table if the soil is saturated from the zone of freezing downward, or it may be derived from the suspended subsurface water retained against the force of gravity above the capillary fringe.

Heaving is apt to be excessive at points where the water table is locally so close to the surface that the capillary fringe extends up into the zone of freezing, but essentially similar conditions obtain if freezing occurs when the soil is temporarily saturated from the freezing zone down to the capillary fringe with downward percolating water from recent rains or from melting snow or ice. If thawing is from the surface downward in the spring the water set free can not escape by downward percolation until after most of the ice has melted. Impermeable frozen soil may therefore establish a temporary, perched water table, and the excessive amount of water thus retained at the surface is available for building up masses of segregated ice in case temperature drops below freezing. Experiments show that the water content of a well consolidated soil does not change while water is being drawn through it from the water table below to build ice layers in the zone of freezing above.

When segregated ice is formed from water retained in the soil above the capillary fringe, the withdrawal of water from one point to form ice at another may at first result in shrinkage, but if the process continues air will enter or expand to fill the voids vacated by water. In freezing tests on samples of white clay containing from 9.5 to 29 per cent water [7] the percentage of the water present that was withdrawn from the lower part of the clay and concentrated in the frozen upper part tended to increase slightly as the amount of water

[7] The percentage of water in soils as used throughout this paper is on the basis of the weight of the wet soil.

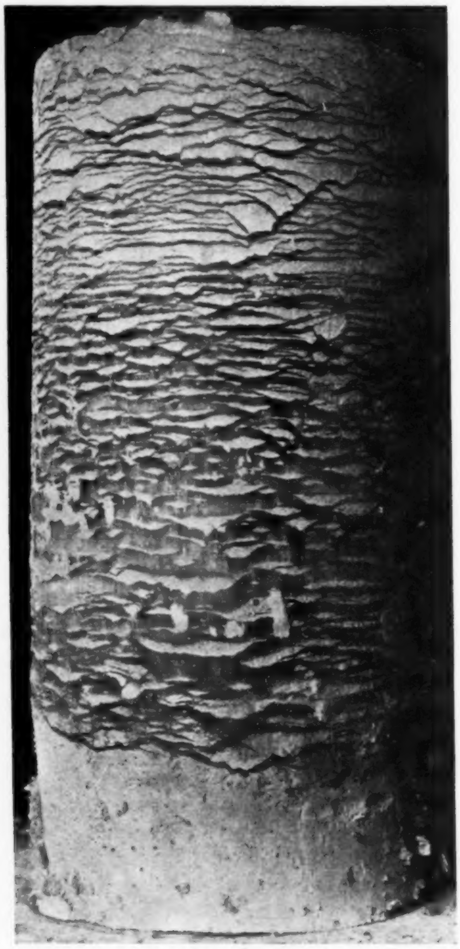


FIGURE 15.—CLAY CYLINDER FROZEN UNDER 30 POUNDS OF IRON SHOWS EXCESSIVE SEGREGATION OF ICE

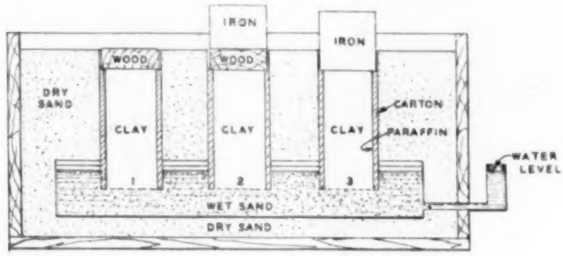
in the soil increased; but even in clays with least water some segregation took place. The porosity of the undisturbed, and therefore thoroughly consolidated, clay used in these experiments is 44 per cent, and when the clay contains about 23 per cent water all of the voids are filled.

REMOVAL OF HEAT DETERMINES EXTENT OF ICE SEGREGATION

When a particular soil having a maximum particle diameter of less than 1 micron is frozen under little or no load in an open system, the amount of segregated ice formed is determined chiefly by the amount by which the heat content of the soil is lowered; and this depends on several factors, such as the length of the cold spell, the minimum temperature reached, the heat present in the soil, and the amount of heat reaching the surface soil from greater depth. The rate at which heat is removed from a soil during freezing, and therefore the rate of heaving, varies according to the conductivity and specific heat of the soil cover.

In one freezing test, iron weights were piled on tightly packed clay to give a pressure of 0.5 kilogram per square centimeter, but, in spite of the pressure, heaving was faster than in similar tests under no load, because of the rapid conduction of heat by the iron. The uplift was 6.4 centimeters and the depth of freezing 15 centimeters after 114 hours in the freezing box. The large amount of segregated ice formed is shown in Figure 15.

In a series of tests carried out to determine the effect of different kinds of soil cover, cylinders of the same size cut from undisturbed clay were used, as greater uniformity could be assured in this way than by packing the pulverized clay. Three of these cylinders were placed in cartons with perforated bottoms and surrounded by paraffin. The cartons stood in sand kept saturated with water as shown in Figure 16. A disk of wood weighing 0.1 kilogram rested on one cylinder, a similar disk of wood and iron weight totaling 3.1 kilograms rested on the second cylinder, while the third was loaded with 3.1 kilograms of iron. The depth of freezing and the ratio of uplift to depth of freezing were both greatest where iron, a good conductor of heat, was in contact with the clay, and were least where wood, which served as a heat insulator, was the only covering. Complete data for the experiment are tabulated under Figure 17, which shows the clay cylinders at the close of the experiment.



CYLINDER NUMBER	1	2	3
LOAD (GMS. PER SQ. CM)	2	60	60
DEPTH OF FREEZING (CM)	8.5	10.0	10.8
UPLIFT (CM.)	3.2	4.1	4.5
RATIO OF UPLIFT TO DEPTH OF FREEZING	0.38	0.40	0.41
TIME IN FREEZING BOX (HRS)	74	74	74
INITIAL TEMP. OF AIR (C)	+16	+16	+16
FINAL TEMP. OF AIR (C)	-14	-14	-14

FIGURE 16.—APPARATUS FOR FREEZING CLAY CYLINDERS WHEN WEIGHTED WITH DIFFERENT MATERIALS

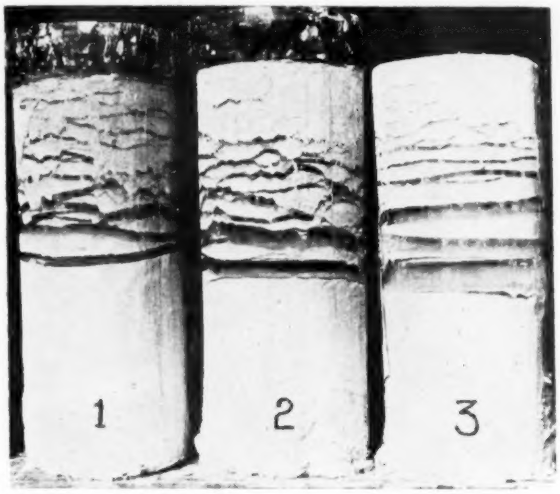
Similar tests were performed on three clay cylinders, one of which supported 7.4 kilograms of iron, while another with the same load had a wooden disk between the clay and iron, and the third had nothing on it. The depth of freezing and ratio of uplift to depth of freezing were again greatest where the iron rested on clay, and they were least where the wood retarded the removal of heat from the clay. (See fig. 18.)

Under moderate loads, therefore, pressure has less influence on the heaving of clay than the thermal properties of the material used in applying the load.

In the six tests described above the ratio of uplift to depth of freezing appears to vary with the rate of heat removal, but the differences in the ratios were not great, and other tests indicate that rapid freezing tends to reduce the ratio of uplift to depth of freezing rather than increase it. These anomalous results were probably due to the fact that less work was required in drawing water up to the growing ice layers in tests where freezing approached close to the water table.

In open systems where heaving is largely if not entirely due to the formation of segregated ice the most favorable places for the development of ice layers are

close to the surface and near the lower limit of frost penetration—points where the freezing isotherm descends the slowest. Ice needles develop at the surface of moist clayey soils when the temperature of the ground immediately below the surface remains above freezing, while the air temperature is below freezing; they do not form when previously chilled soils are rapidly frozen during a sudden drop in temperature. Under



	Cylinder No.		
	1	2	3
Height of cylinder before freezing...centimeters..	14.3	14.3	14.3
Diameter of cylinder...do....	7.8	7.8	7.8
Load, grams per square centimeter...	2.0	60.0	60.0
Depth of freezing...centimeters..	8.5	10.0	10.8
Uplift...do....	3.2	4.1	4.5
Ratio of uplift to depth of freezing...	0.38	0.40	0.41
Time in freezing box...hours..	74.0	74.0	74.0
Initial temperature of air...° C..	+16°	+16°	+16°
Final temperature of air...do....	−14°	−14°	−14°

Figure 17.—Clay Cylinders Frozen Under Loads as Shown in Figure 16

similar conditions thin layers of ice form under stones and pavements.

In material barely fine enough to permit segregation, such as the barium sulphate previously described, well-defined layers of ice may develop only near the top and at the bottom of the frozen material. (See figs. 9, C and 9, D.)

The absence of well-defined ice layers near the top of the test specimen shown in Figure 9, D was due to rapid conduction of heat by a 4-pound iron weight that rested on it during the experiment. The formation of ice layers was entirely prevented by packing the carton of barium sulphate, together with the wet sand in which it stood, in ice for 18 hours to bring the system to 0° C., and then transferring it quickly to the sand box, which had been brought to approximately the same temperature. Under these conditions the freezing isotherm moved rapidly downward as the air temperature in the refrigerator was about −15° C. Finer material, when treated in this way, was not appreciably affected, and ice layers developed about as usual.

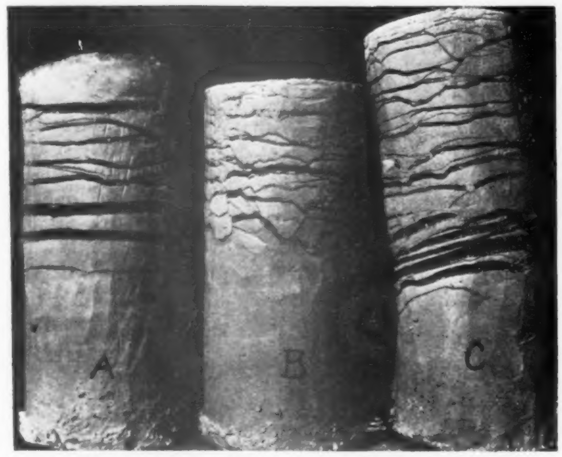


Figure 18.—Clay Cylinders Frozen (A) Under no Surface Load, (B) Under Iron Weight Insulated from Clay by Wooden Disk, and (C) Under Iron Weight in Contact with Clay

SURFACE LOAD AFFECTS ICE SEGREGATION

A relatively small surface load will entirely prevent frost heaving in an open system if the material is of such texture that only a little segregated ice forms under the most favorable conditions. A pressure of 2.11 kilograms per square centimeter prevented ice segregation and frost heaving in the barium sulphate (particle diameter 2 microns), but similar pressures resulted in very little reduction of heaving in kadox (particle diameter one-fourth micron) or in the pure white clay.

A cylinder cut from undisturbed clay and frozen under a surface load of 3.52 kilograms per square centimeter is shown in Figure 19. In some of the tests on silts and gritty clays a little heaving occurred under no surface load while material within an inch or two of the surface was being frozen, but as freezing progressed downward the friction of the frozen soil against the walls of the container was sufficient to stop ice segregation and therefore heaving.

Apparatus devised to measure pressures developed during the freezing of soil in an open system is shown in Figure 20. A carton containing the soil stands in sand kept saturated with water, and a spring, resting on top of the soil, is compressed against a steel plate as heaving takes place, the amount of uplift and the pressure developed being indicated on a scale by a wire pointer that extends up through the spring. The carton shown in the photograph had been strengthened with tape saturated with shellac. The wooden boards fit snugly around the carton and hold it rigidly in place.

The results of a test made on tightly packed clay are shown in Figure 21. The carton stretched somewhat under the high pressure both above and below the board that surrounded it, and this explains the more or less vertical ice veins. The maximum pressure measured was 7.31 kilograms per square centimeter, but this figure does not take into account the frictional resistance of the frozen clay in contact with the container, which must have been high.

In a test with a cylinder 13 centimeters high and 5 centimeters in diameter cut from undisturbed clay and

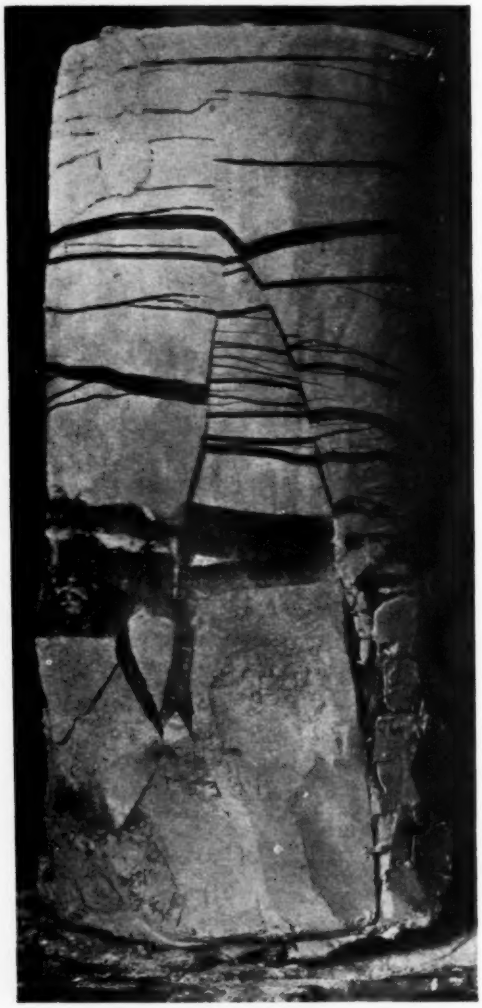


FIGURE 19.—CLAY CYLINDER FROZEN UNDER A LOAD OF 3.52 KILOGRAMS PER SQUARE CENTIMETER WHILE STANDING IN WET SAND

surrounded with paraffin, a pressure of 11.25 kilograms per square centimeter was obtained. The layers of segregated ice were few and small, the maximum thickness being about 1 millimeter. In tests performed under slightly higher pressure heaving was almost imperceptible.

Only rough estimates can be made of the maximum pressure developed, for to the surface load lifted it is necessary to add the force required to separate the clay cylinder, and also the frictional resistance to heaving which is not a factor when soils freeze in the ground. Moreover, an ice layer must begin to form at some favorable point and then spread outward rather than form across the entire cross section of the cylinder instantaneously. The clay used in these tests, as it comes from the mine, has a tensile strength of about 5 kilograms per square centimeter. Therefore, the maximum pressure was probably well over 14 kilograms per square centimeter, but it is doubtful if it appreciably exceeds 15 kilograms per square centimeter.

The amount of heave in open systems decreases with increase in pressure, and the maximum load which may be lifted increases with decrease in particle size. With finer material it should be possible to lift somewhat heavier loads, but with much decrease in size of particle the material would approach colloidal dimensions and become highly impermeable. Lack of permeability may be compensated for in part by slower freezing.

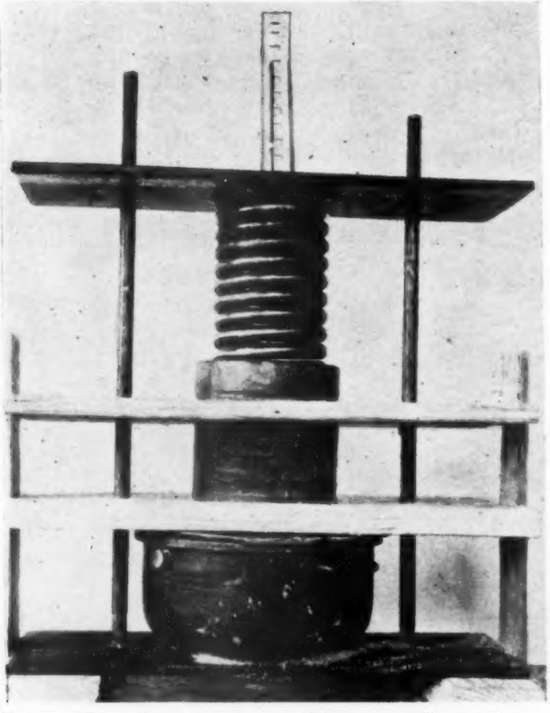


FIGURE 20.—APPARATUS FOR FREEZING CLAY CYLINDERS UNDER PRESSURE

The limit to the load that may be lifted by frost heaving in an open system is not due to inability of ice crystals to grow under higher pressure, but to the failure of the water supply. This fact was demonstrated by supplying the water under greater pressure. The upper part of a strong container was filled with well-compacted moist clay and the lower part with water. (See fig. 22.) They were separated by a perforated disk of hard rubber, with filter paper resting on top, the disk being supported by a steel spring resting on the bottom of the container. The lower part of the container stood in a can of impervious cement, while the upper part was strengthened by surrounding it with wood strips held in place by steel bands.

The apparatus was placed in the refrigerator and buried to the top of the container in dry sand. A pressure of 14 kilograms per square centimeter was applied to the clay by means of a piston inserted in the top of the container, the pressure being measured by the compression of a calibrated spring. Because of the resistance of the smaller spring the water in the bottom of the container was under a pressure of less than 10 kilograms per square centimeter. As freezing progressed water was drawn into the clay to form ice layers and the springs were compressed until the final pressure on the clay was about 15 kilograms per square centimeter. The total thickness of the ice was between 2 and 3 centimeters (see fig. 23) whereas almost no heaving could be obtained when this clay was frozen under similar pressures but with the water under atmospheric pressure only.

THE MECHANICS OF FROST HEAVING IN OPEN SYSTEMS DISCUSSED

The mechanics of the process by which ice crystals, growing in open systems, are able to exert pressure and

overcome resistance has been discussed in some detail in a recent paper [8] from which the following account is largely abstracted.

In indurated clay, or in clay that has been thoroughly consolidated artificially, the layers of segregated ice are clear (for the most part), solid, and very sharply separated from the clay. The ice usually shows a satiny

FIGURE 21.—TIGHTLY PACKED CLAY FROZEN UNDER A LOAD OF 7.31 KILOGRAMS PER SQUARE CENTIMETER

luster because of the parallel orientation of the ice prisms and the presence of small filiform cavities filled with air, oriented in the direction of crystal growth. Both thickness and spacing of the ice layers tend to increase with distance from the cooling surface. The total thickness of the ice layers, as close as can be measured, equals the amount of surface uplift; and the water content of frozen clay between the ice layers is the same as that of clay below the depth of freezing. These observations prove that heaving in such tests is due to the formation of ice layers, the freezing of interstitial water being of little or no importance. In the test shown in Figure 14, A a sample taken just below the frozen material and three samples taken between successive ice layers gave 22, 22.1, 21.8, and 22 per cent water, respectively. Heaving was as uniform (see fig. 24) and not intermittent, which proves that a new ice layer began to form below as soon as the layer immediately above stopped growing.

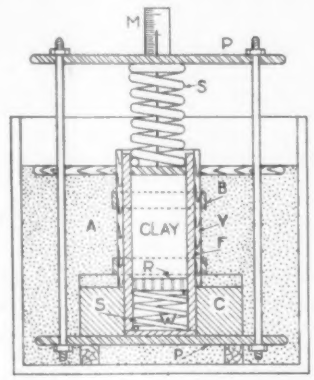
In tests with unconsolidated clays the ice layers were not so sharply defined, and, in most cases, it was not possible to estimate accurately the thickness of the ice, but, here also, heaving must be due primarily to the formation of segregated ice.

[8] Stephen, Taber, "The Mechanics of Frost Heaving," Jour. of Geol., Vol. XXXVIII (1930), pp. 303-317.

"A growing ice crystal is in contact with a thin film of water similar to the adsorbed layer which forms on many other solids that are in contact with water. As a molecule in the film is oriented and attached to the crystal it is replaced by another from the adjacent liquid, thus maintaining the integrity of the film. If resistance to growth is offered by a solid body such as a soil particle, the pressure is exerted through the thin film of water that separates them. This film may consist of a single layer of molecules; but I am inclined to think that it is somewhat thicker, for the molecules in it possess considerable mobility. A unimolecular layer could not be expelled by pressure alone; thicker layers could be reduced through expulsion of some of the molecules under pressure, though this is probably resisted by the strong attractive forces. After the available water has been exhausted the film may be frozen, but it does not freeze readily.

"The orientation and attachment of a molecule to the crystal is accompanied by a slight repulsion, proportional to the change in volume; but this can not be considered an essential factor in the process, for liquids that freeze with decrease in volume give pressure effects in open systems similar to those obtained with water.

"Cohesion is greater between the molecules in the films and between these molecules and the ice than it is between water molecules that are not similarly located close to ice crystals. Since no outside force is competent to push molecules of water into the film between the growing ice crystal and the resisting solid, the crystal must be displaced relative to the adjacent solid because water is pulled in between them; and this is made possible by the high intermolecular attraction, which prevents the separation of the water molecules.



A—DRY SAND
B—STEEL BANDS
C—CEMENT
F—FIBER CONTAINER
M—GRADUATED SCALE
P—STEEL PLATE
R—HARD RUBBER DISK
S—STEEL SPRING
Y—WOOD STRIPS
W—WATER

FIGURE 22.—APPARATUS FOR FREEZING CLAY UNDER HEAVY PRESSURE WITH RESERVOIR OF WATER UNDER LESS PRESSURE

"* * * Since ice crystals growing in an open system are able to overcome a resistance many times as great as atmospheric pressure, the water in such cases is actually pulled into the nourishing film under high tension.

"* * * A water column of large cross section is placed under tension with difficulty, for the water is superheated when under negative pressure, even at temperatures below 0° C., and the formation of a gas phase immediately breaks the column. Extremely slender columns or filaments and thin films are more

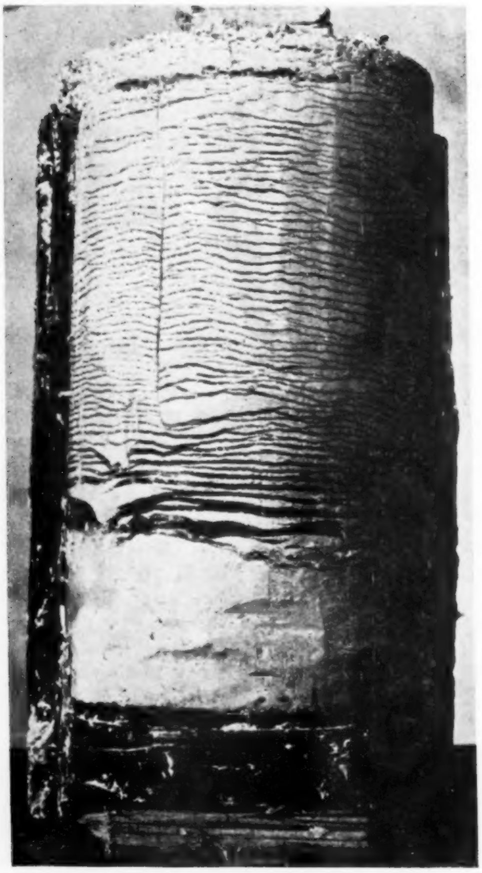


FIGURE 23.—CLAY FROZEN UNDER PRESSURE OF 15 KILOGRAMS PER SQUARE CENTIMETER IN THE APPARATUS SHOWN IN FIGURE 22

easily maintained under tension than larger ones, and this is the form in which water is present in clays.

"* * * during the growth of an ice layer the voids in the adjacent underlying clay, beginning with the larger ones, tend to fill gradually with ice and thus increase the work that must be performed in supplying water to the ice layer. When resistance becomes too great the flow of water to this ice layer stops and a new layer of ice begins to form near the bottom of the zone of frost penetration. More of the water in the clay between the ice layers freezes as the temperature gradually becomes lower, some of it possibly migrating to the ice layers; * * *

"An ice prism in one of the layers continues to grow at the base where it is exerting pressure against an adjacent soil particle as long as water molecules can enter the separating film and be attached to the crystal. If the soil particle is very small, the molecules travel only a short distance through the film to reach the points where they are attached. If the soil particle is larger, it takes longer for the molecules to reach their points of attachment; and meanwhile freezing may extend downward around the particle so as gradually to inclose it in ice. As soon as crystal growth is checked at any point the temperature of the adjacent soil particle begins to fall, for heat is no longer liberated at this point by the conversion of water into ice; and since water is a poorer conductor of heat and has a higher specific heat than the minerals present in soils, the temperature of the bottom of the soil particle will reach

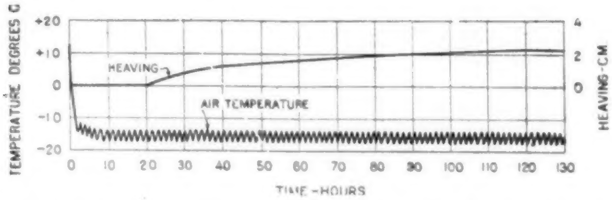


FIGURE 24.—GRAPHS SHOWING AIR TEMPERATURE AND RATE OF HEAVING DURING FREEZING OF THE CLAY CYLINDER SHOWN IN FIGURE 14, A

the freezing point sooner than the water with which it is in contact. This helps to bring about the inclusion of the soil particle in the ice. The formation of layers of segregated ice is possible only when the soil particles are excluded by the growing crystals, a process which is aided by slow freezing, for then the molecules have more time in which to penetrate between crystal and soil particle."

The growth of ice layers is stopped by lack of water supply, which may be due to rupturing of the upward moving filaments and films of water under tension or to the inability of molecules to enter films that are under pressure. Pressure tends to reduce the thickness of the nourishing film by expelling some of the molecules, and since the expulsive forces are increased the attractive forces must likewise be increased by lowering the temperature, else molecules can not enter the film. Pressure decreases molecular mobility in the film, retards crystal growth, and lowers the freezing point. The growth of ice crystals under pressure in open systems is possible because water occupying very small voids can be undercooled.

FREEZING OF SOIL A FACTOR IN THE DESTRUCTION OF PAVEMENTS

Uniform heaving of the subgrade results in little or no damage to pavements, but differential heaving may be very destructive, especially to thin, weak pavements and to those that are badly worn. The factors which determine frost heaving, such as texture and composition of soil, water supply, rate of freezing, and pressure, have all been discussed above. Local differences in any of these factors will tend to cause differential heaving; but differences in the soil and in the amount of water available are probably the commonest causes.

The importance of difference in soil texture is illustrated by the following experiments. A carton with perforated bottom was tightly packed with fine sand on one side and clay on the other, by inserting a partition down the middle and gradually withdrawing it as the soils were tamped into place. The carton stood in sand which was kept saturated with water throughout the experiment. After the soils had become moist on top the carton was buried to the top in dry sand, so that freezing took place from the top down. At first only the clay was appreciably heaved, but when the frozen crust became thicker, and therefore stronger, the sand was lifted along with the clay. As layers of segregated ice developed the underlying unfrozen clay was pushed down and under the sand, thus helping to force it up. The experiment was discontinued after the bottom of the carton had been forced out and to one side by the movement of the clay, as shown in Figure 25, A. If this experiment could have been made on a large enough scale no heaving of the sand would have occurred except in the immediate vicinity of its contact with the clay.

Another experiment was performed in the same way except that after the sand and clay had become saturated with water the carton was sealed at the bottom by standing it in a tray of molten paraffin. On freezing, layers of clear ice developed in the clay (see fig. 25, B), the water to form them being drawn out of the clay in the lower part of the carton and also from the sand. The withdrawal of water resulted in the formation of shrinkage cracks in the lower part of the clay, and the lower half of the sand was so nearly dry that it flowed readily. The large cavity shown in the photograph was caused by the dislodgment of dry sand, and more of the sand collapsed just after the picture was taken. The upper part of the sand was thoroughly cemented by ice which filled all voids. Because of differential heaving the frozen soil cylinder was gradually tilted away from the clay side, causing the wall of the carton to pull apart by tension. The inclination of the ice layers downward toward the sand may be in part due to this tilting, but it is largely to be explained by the fact that the freezing isotherm moved downward faster in the sand, where less water was being frozen than in the clay, so that some heat was conducted laterally from the clay into the sand.

These experiments show that, as a result of frost heaving, pavements are likely to be cracked and the sections differentially displaced at places where the subgrade soil changes from sand to clay, a change that occurs rather frequently in parts of the glaciated region. Also, where there are lenses of clay in sand, or vice versa, the excessive heaving over the clay may be caused by water drawn in part from the adjacent sand.

Since pressures of nearly 15 kilograms per square centimeter may be obtained through the freezing of pure clays in systems that are open with respect to water, a small mass of clay inclosed in nonheaving subgrade material may result in the uplift of a relatively large section of pavement, and thus subject it to stress sufficient to cause rupture. When sections of pavement are separated from the subgrade by differential heaving, air enters to form an insulating layer that retards the freezing of soils at these places as compared with those where the soil remains in contact with the pavement. As a result of differential heaving, pavements have sometimes been separated from the subgrade so that it was possible to see from one side of the highway to the other under the pavement. These facts emphasize the necessity of thoroughly mixing the subgrade material so as to make it uniform in texture and composition.

The amount of heaving that accompanies the freezing of soil is limited by the supply of water available, including the water which may be drawn from below the depth of freezing as well as that which was originally present. A uniformly dry subgrade does not heave and a uniformly wet one would result in uniform rather than differential heaving. Local differences in the moisture content of soils and especially differences in the position of the water table relative to the surface are important as causes of differential heaving. This condition may frequently be remedied by drainage designed to lower the water table under subgrades where it comes too close to the surface, but deep drainage is necessary in soils where the capillary fringe rises high above the water table.

Local differences in the rate of cooling due to differences in soil cover are a minor cause of differential frost heaving. Ordinarily the soil forming the shoulders of a road, if wet, will begin to freeze before the soil lying under the pavement; but when the ground is dry, or is covered with snow while the pavement is cleared for traffic, the reverse would be true. In suitable soils the water will be drawn toward those points where freezing is going on and away from those areas where freezing has not begun.

When the road shoulders begin to heave before soil freezes under the pavement, the latter may possibly be lifted because of cohesion between frozen soil and pavement. This would result in the introduction of an insulating layer of air between pavement and subgrade, which would further retard freezing under the pavement.

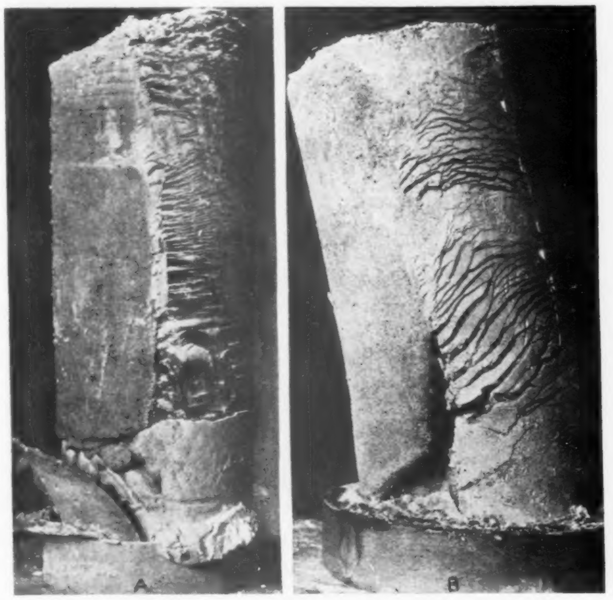


FIGURE 25.—EXPERIMENTS SHOWING DIFFERENTIAL EFFECTS OF FREEZING IN SAND AND IN CLAY. A.—FROZEN CYLINDER HALF SAND AND HALF CLAY. MUCH SEGREGATED ICE IN CLAY BUT NOT IN SAND. B.—DIFFERENTIAL DISPLACEMENT OF CYLINDER, DUE TO SEGREGATION OF ICE IN CLAY BUT NOT IN SAND. CAVITY CAUSED BY DISLODGMENT OF DRY SAND

The process is easily illustrated experimentally. A smooth rectangular block of iron was embedded in clay so as to be flush with the surface, the clay being packed in a large carton which stood in wet sand. When heaving began the iron block was not, at first, displaced with reference to the surface, for it was lifted from its bed with the formation of an air pocket below. Two days later, because of slow vaporization of the ice, cohesion between the smooth metal and the frozen clay was reduced, and the block dropped into the pocket so that it was 1.3 centimeters below the surface of the clay.

From the meager observations that the writer has been able to make, it seems likely that heavy cement pavements are seldom if ever lifted because of heaving of soil forming the shoulders; but this is a question requiring further field investigation. The differential heaving of subgrade and shoulders does, however, help to explain the breaking up of asphalt macadam and surface treated roads along the edges.

After a road surface becomes badly worn and pitted, heaving of the subgrade will begin at those points where the pavement is thinnest, and gradually lift it until an insulating air layer surrounds the area of heaving. As heaving continues the stresses tending to cause fracture increase until sooner or later weak

pavements collapse around the point of uplift. This is probably the explanation of most of the so-called frost boils that form on asphalt macadam and other relatively weak types of road surfacing, but frost boils may also be caused by differential heaving due to local differences in the texture and composition of the subgrade soil.

THAWING OF SOIL ALSO A FACTOR

Experiments prove that freezing tends to concentrate water near the surface even when the soil contains relatively little water. Under favorable conditions excessive quantities of water may be drawn upward and concentrated near the surface in the form of segregated ice. More water can be introduced into a soil that is in place in this way than by any other natural process. When thawing occurs this excessive amount of water may be disposed of in two different ways.

1. If the air temperature remains barely below freezing for a long enough time, a deeply frozen soil will thaw gradually from the bottom, because of the outward conduction of heat from the interior of the earth, and the water may then return to the underground reservoir from which it was drawn. But since water is pulled toward the surface during the freezing process by a force that is greatly in excess of the forces causing its downward movement in soil, the water may not be removed as rapidly as melting takes place unless the latter is very slow.

2. On the other hand, if the air temperature is well above 0° C. so that melting occurs from the surface, the water set free can not escape downward through soil voids until thawing is practically complete. Under these conditions the water has to remain in the soil until it can drain out to the surface and flow away, which is a rather slow process.

The thawing of deeply frozen soil, of course, usually takes place from both top and bottom, but sometimes one type of thawing predominates and sometimes the other. When a soil containing much segregated ice thaws rapidly from the top because of a sudden rise in air temperature, the soil becomes supersaturated with water.

A heavy snow fall before the ground freezes forms a protective blanket, and if the ground remains well covered throughout the winter relatively little soil freezing occurs. Even though the snow comes after the ground has frozen to a considerable depth, it may prevent rapid removal of heat, and therefore enable the soil to thaw slowly at the bottom of the zone of frost penetration. If the snow melts rapidly in the spring much of the water runs off on the surface and comparatively little enters impervious clay soils. The soil may become saturated close to the surface, but it does not become supersaturated, as may happen when segregated ice melts. This explains why common dirt roads in areas of clayey soil are usually in worse condition after a spring thaw that follows an open winter than after a winter when the ground has been heavily blanketed with snow.

It is difficult for water from rain or melting snow to accumulate immediately under impervious pavements in quantity sufficient to saturate the soil, especially where reasonably good drainage has been provided; but as a result of freezing where the conditions are favorable, water sufficient to supersaturate the soil may be concentrated under the pavement. Keeping pavements cleared of snow while the ground on each side is buried should increase the amount of segregated ice formed under the pavements, for water may then be drawn in part from the soil at the sides.

Since the mobility of soils under stress is increased by the presence of excessive amounts of water, superficial landslides occasionally occur during spring thaws. Clay containing much water will creep or flow out from under a heavy weight, such as a pavement, causing it to slowly settle. Where drainage facilities are good, so that water from a melting ice layer escapes rapidly, soil particles may be entrained and carried out with it.

Slow removal of material from under a pavement by soil creep or by entrainment of particles in draining water results in unequal settling, but cracks due to this cause may develop only under heavy traffic, perhaps long after the freezing and thawing occurred. Some cracks are probably due to the cumulative effects of several seasons of freezing and thawing. Unequal settlement after thawing has not been appreciated as a cause of the failure of pavements.

Rapid thawing from the surface downward, in soils where segregated ice forms, tends to accentuate all of the engineering troubles ordinarily associated with poor drainage, but methods of draining that satisfactorily protect road pavements in warm regions may be inadequate on some soils in regions of deep frost penetration.

THAWING AND REFREEZING DESTRUCTIVE TO ROAD PAVEMENTS

The formation of segregated ice in soils, which often results in differential heaving, is favored by a high water content, for water is then immediately available for the growth of ice crystals. Subgrade soils, protected by impervious pavements, are not easily saturated by rains or by water from melting snow, if ordinary drainage has been provided; but in suitable soils under favorable conditions water may be pulled up from below and concentrated under a pavement in the form of ice, which, on melting, may set free sufficient water to saturate or even supersaturate the soil. Therefore, a sudden drop in temperature after a spring thaw has left an excessive amount of water in the soil is apt to be more destructive to pavements than the slow freezing of an entire winter.

The effects of refreezing after a thaw are also accentuated by the fact that the first freeze leaves the soil in a more or less loosened or expanded condition. Experiments have demonstrated that heaving is greater on unconsolidated clays than on those that are thoroughly consolidated. Bituminous macadam and other relatively weak types of surfacing material seem to be especially susceptible to differential heaving brought about by a sudden freeze after a spring thaw.

DISTRIBUTION OF DAMAGE BY FROST HEAVING ERRATIC

Engineers have found it difficult to explain the apparently erratic distribution of damage from frost heaving. A pavement may be badly damaged the first winter after it is laid and then suffer relatively little injury from frost heaving during a series of succeeding winters. Other pavements are sometimes seriously damaged after having passed through several winters with little or no trouble. In one locality a certain type of soil may give much trouble while in another locality roads constructed on the same type of soil are said to be virtually immune to frost action. These apparent inconsistencies arise largely from the fact that damage by frost heaving is controlled by not one but several variables.

A new pavement may sometimes suffer greater damage from frost heaving because the subgrade soil has not become thoroughly consolidated. Repeated tests have shown that the rate of heaving and the ratio of heaving to depth of freezing are much greater on loosely consolidated soil, than on the same material when thoroughly consolidated. (Compare the tests shown in figs. 14, A and 14, B.) Some pavements suffer little damage until after they have become weakened or worn and pitted from service.

With the same soil and locality the heaving varies greatly during different winters because of differences in the position of the local water table, differences in precipitation, and differences in temperature. And in considering temperature differences, the length of a cold spell and the minimum temperatures reached may often be less important than the fluctuations in temperature that bring about freezing and thawing and result in the concentration of water near the surface.

Some winters little soil freezing occurs because of a protective blanket of snow, while during open winters frost penetration is relatively deep.

In a flat region where the water table practically parallels the surface and there is no appreciable variation in the texture and composition of the soil over large areas, such heaving as occurs is likely to be uniform, and therefore to cause little damage to pavements. In another area, having the same type of soil but more relief, the depth of the water table will vary; and this, as well as other factors, causes differences in the available water supply, and consequently differential heaving.

OBJECTS BURIED IN SOIL SOMETIMES DISPLACED BY FREEZING AND THAWING

When soils, because of freezing and thawing, become supersaturated with water, buried objects, especially if smooth and of high specific gravity, tend to sink. This downward displacement at the time of a single thaw is usually small, but repeated freezing and thawing bring about appreciable effects. This probably explains the gradual settlement of gravel from under pavements that has been observed in certain districts.

During the heaving of a soil, cavities tend to form immediately over buried objects because less segregated ice forms there than at points where impermeable material does not separate growing ice crystals from the water supply.

When a large object is gripped in frozen soil and lifted from its bed by heaving, a cavity develops beneath. Soil may accumulate in the cavity while the object is suspended, especially if thawing takes place chiefly from the bottom of the frozen layer, so that the object can not settle back to its former position. This is probably the main factor in causing certain objects, such as culverts, gradually to work upward toward the surface.

METHODS OF DETERMINING THE RELATIVE HEAVING PROPERTIES OF SOILS DESCRIBED

In order that suitable precautions may be taken it is often desirable to ascertain how a soil will behave when subjected to freezing, and in this connection the most important fact to be determined is the amount of heaving that can occur when freezing conditions are most favorable. It has been shown that the texture and composition of a soil, and especially the percentage of clay present, are the main factors. When known they give a pretty good indication of how the soil will behave. A larger number of freezing tests, accompanied by complete physical analyses on a greater variety of soils, should make it possible to forecast with some accuracy the behavior of a soil on freezing.

In the present investigation two methods have been devised for measuring the relative heaving qualities of soils. The first method used was to determine the ratio of surface uplift to depth of freezing. It may be used whenever it is possible to measure accurately the amount of heaving. The main objection to the method is the difficulty of determining the exact depth of frost penetration in clays, and in laboratory tests, which are limited in duration to a few days, this difficulty may introduce a relatively large error. Also, it is not, as a rule, possible to remove a test from the refrigerator as soon as heaving stops.

The second method is based on the rate of heaving. Most soils, when frozen at constant air temperature in the apparatus described above (see fig. 3), heave uniformly for several hours after freezing begins, so that the graphs drawn by the recording pen are nearly straight lines. These graphs would have shown more curvature if it were not for the fact that the containers were surrounded by dry sand which did not heave.

Where either method is used, strictly comparable results can be obtained only when every precaution is taken to perform the tests under exactly the same conditions of cooling, of water supply, and of resistance to heaving, which includes friction between soil and container as well as surface load. To insure similar conditions of cooling, the soil containers should be the same height above the floor of the refrigerator box so that there will be the same amount of insulating material under them; and the initial temperature of the soil, the minimum temperature, and the rate at which the surface temperature drops should all be the same. Differences of only a few degrees in the room temperature produce no appreciable effects.

Frictional resistance between soil and container varies considerably with different soils, and as yet no satisfactory method of equalizing this factor has been found. When soils freeze in the ground frictional resistance is seldom a factor. In a few tests there was a tendency for the soil to push out the bottom of the container and displace the underlying sand, but a method has been devised which will obviate this difficulty in future tests.

South Carolina Cretaceous white clay was used in most of the preliminary freezing tests because it is a very pure kaolin, uniform in texture, and practically free from grit. Tests with this clay also photograph well. As compared with other soils that have been tested, its rate of heaving is exceptionally high, although the clay from St. Peter, Minn. (see p. 116), closely approaches it. The latter heaves at the rate of 0.76 millimeter per hour while the South Carolina clay under the same conditions heaves 0.83 millimeter per hour.

MEASURES DISCUSSED FOR PREVENTION OF DAMAGE CAUSED BY FREEZING AND THAWING OF SUBGRADE SOILS

No panacea can be prescribed for all of the ills associated with the freezing and thawing of soils. Rather, each locality where frost heaving is troublesome should be treated as an individual problem, for a satisfactory solution in one place may prove impractical in another. It is now possible to determine by laboratory tests the relative heaving properties of soils, but in each case a field investigation is necessary to determine the other

factors involved in frost heaving, such as the possibility of freezing taking place as in a closed system and the probability of water being available for excessive heaving.

Some places which are subject to excessive differential heaving can be avoided in locating the highway, but in most cases this would be impractical. The use of smaller and stronger sections reduces cracking but does not prevent spalling and unevenness at the joints due to differential displacement. Better drainage is often beneficial, though drainage alone will not remove water occupying extremely small capillary voids in soil, or prevent the drawing up of more water during the growth of ice crystals.

Sodium silicate mixed into clay lowers the freezing point, increases the percentage of water that does not freeze, and reduces permeability. In practical use it would be slowly leached out of soils that are alkaline. In acid soils sodium silicate decomposes with the precipitation of insoluble gelatinous silica, which on drying would act as a cement and help to bind the soil particles together. The presence of carbon dioxide in the ground water would be sufficient to bring about the precipitation of the silica.

The troubles resulting from the formation of segregated ice under pavements can be entirely prevented if, in addition to the usual methods of draining, a thick layer of coarse material is introduced under the pavement extending down to the extreme depth of frost penetration. The only objection to this method is the cost, but in those localities where heaving is bad and the expenditure is warranted it should be used.

Addition of sand to the subgrade material will prevent ice segregation, and, fortunately, many soils naturally contain sufficient sand. On soils that do not heave readily the weight of the pavement becomes a factor in preventing uplift. The admixture of colloidal material, such as bentonite, reduces heaving by decreasing permeability, but the increase of colloids in a soil tends to cause greater swelling and shrinking when water is absorbed or lost by evaporation. Uniformity of texture in subgrade soils is essential if differential heaving is to be avoided, and this end can usually be obtained by care in mixing when additional material has to be introduced.

In the future solution of problems connected with the freezing and thawing of soils the most promising opportunities for research at the present time lie in field investigations. Accurate observations are needed, under widely varying conditions in different parts of the country, of the topography, the distribution and occurrence of ground water, and other pertinent factors at points where heaving is excessive and also at points where little or no heaving occurs on soils favorable for ice segregation. The investigations can best be made by geologists who are familiar with the occurrence and movement of ground water in different types of soil and who have studied the processes involved in frost heaving.

ENGINEERS FROM ALL PARTS OF WORLD TO PARTICIPATE IN INTERNATIONAL ROAD CONGRESS

More than 50 nations have accepted the invitation of the United States Government to participate in the Sixth International Road Congress to be held in Washington, October 6 to 11, and officials in charge are entering the final stage of their preparations to receive the large number of delegates expected.

The congress will be held under the auspices of the Permanent International Association of Road Congresses, with headquarters in Paris, and under the immediate direction of the American Organizing Commission, Roy D. Chapin, president, with offices in Washington.

Seventy-six separate reports, printed in French, German, Spanish, and English, the four official languages of the congress, will form the basis for discussion at the sessions in October. The reports represent the studied opinions of 170 of the principal world authorities on the moot questions of highway construction, design, material, maintenance, administration, finance, and traffic.

More than a year ago the several topics to be studied at the congress were decided upon and the chief exponents of the various questions assigned to write upon them. The result has been a series of articles and papers that represent most that is known to-day of the twin sciences of highway cosntruction and automotive transportation.

For months a corps of translators has been engaged in the task of preparing the reports to the congress in four different languages. The English and Spanish translations have been made in Washington under the supervision of engineers and editors of the United States Bureau of Public Roads, while the French and German versions have been made in Paris under the immediate direction of M. Le Gavrian, secretary-general of the association.

With the task of translation and printing completed, the reports are being mailed to the far corners of the earth, so that delegates coming to Washington this autumn may fortify themselves to support or to attack the theories and conclusions set forth in the reports. Each member of the association will receive a collection of the reports in that one of the four languages with which he is most familiar. Membership in the association is essential to participation in the congress.

The net result of this distribution will be an intensive, simultaneous world study of highway problems preparatory to the serious discussions of the congress itself. Following the congress, the proceedings, containing the debates, will likewise be published in the four languages.

Seven general reporters have consolidated the individual papers, giving extensive résumés of the discussions on the six major questions on the agenda.

AMERICAN ENGINEERS URGED TO ATTEND CONGRESS

Highway engineers and officials and representatives of organizations and industries interested in highway construction and transporation are urged to attend the congress. A temporary membership may be obtained through the American Organizing Commission, 1723 N Street NW., for $5. The volume of reports and general conclusions is now being distributed to all classes of members and these reports are available only to members of the congress.

Details concerning membership in the congress, the agenda of the congress, and the program which has been adopted will be found in the two preceding issues of PUBLIC ROADS.

ROAD PUBLICATIONS OF BUREAU OF PUBLIC ROADS

Applicants are urgently requested to ask only for those publications in which they are particularly interested. The Department can not undertake to supply complete sets nor to send free more than one copy of any publication to any one person. The editions of some of the publications are necessarily limited, and when the Department's free supply is exhausted and no funds are available for procuring additional copies, applicants are referred to the Superintendent of Documents, Government Printing Office, this city, who has them for sale at a nominal price, under the law of January 12, 1895. Those publications in this list, the Department supply of which is exhausted, can only be secured by purchase from the Superintendent of Documents, who is not authorized to furnish publications free.

ANNUAL REPORTS

Report of the Chief of the Bureau of Public Roads, 1924.
Report of the Chief of the Bureau of Public Roads, 1925.
Report of the Chief of the Bureau of Public Roads, 1927.
Report of the Chief of the Bureau of Public Roads, 1928.
Report of the Chief of the Bureau of Public Roads, 1929.

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Report of a Plan of Highway Improvement in the Regional Area of Cleveland, Ohio.
Report of a Survey of Transportation on the State Highways of Pennsylvania.

REPRINTS FROM THE JOURNAL OF AGRICULTURAL RESEARCH

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Vol. 5, No. 19, D- 3. Relation Between Properties of Hardness and Toughness of Road-Building Rock.
Vol. 5, No. 24, D- 6. A New Penetration Needle for Use in Testing Bituminous Materials.
Vol. 6, No. 6, D- 8. Tests of Three Large-Sized Reinforced-Concrete Slabs Under Concentrated Loading.
Vol. 11, No. 10, D-15. Tests of a Large-Sized Reinforced-Concrete Slab Subjected to Eccentric Concentrated Loads.

* Department supply exhausted

UNITED STATES DEPARTMENT OF AGRICULTURE

BUREAU OF PUBLIC ROADS

CURRENT STATUS OF FEDERAL AID ROAD CONSTRUCTION

AS OF

JULY 31, 1930

STATE	COMPLETED MILEAGE	UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					BALANCE OF FEDERAL-AID FUNDS AVAILABLE FOR NEW PROJECTS	STATE
		Estimated total cost	Federal aid allotted	MILEAGE			Estimated total cost	Federal aid allotted	MILEAGE				
				Initial	Stage[1]	Total			Initial	Stage[1]	Total		
		$	$				$	$				$	
Alabama	2,186.0	1,481,006.51	727,341.56	66.0	8.2	74.2	13,545.40	6,772.70				4,138,887.66	Alabama
Arizona	819.4	3,941,758.03	2,958,897.65	128.2	149.5	277.7	88,816.86	66,870.19	4.0	3.6	7.6	1,891,906.00	Arizona
Arkansas	1,744.8	5,686,289.28	2,830,989.23	170.6	42.8	213.4	1,685,042.02	840,548.39	62.0	12.6	74.6	1,389,142.48	Arkansas
California	1,884.3	7,084,139.11	2,932,920.86	122.8	27.8	150.6	2,836,368.65	1,312,098.03	70.9	2.2	73.1	1,066,922.41	California
Colorado	1,183.2	5,130,165.48	2,695,453.16	184.1	69.4	253.5	870,833.80	418,069.68	24.3	27.8	52.1	2,238,694.69	Colorado
Connecticut	243.3	2,596,633.60	1,099,282.57	14.0		14.0	670,974.87	158,615.00	10.5		10.5	823,875.34	Connecticut
Delaware	281.7	1,030,916.80	496,933.02	50.3		50.3	135,092.62	67,546.31	7.0		7.0	83,675.16	Delaware
Florida	503.5	5,127,463.61	2,358,944.67	97.1	5.5	102.6	501,391.49	250,695.73	4.7		4.7	1,434,128.63	Florida
Georgia	2,671.3	5,047,427.55	2,396,378.67	152.0	81.2	233.2	1,718,614.31	812,471.03	41.0	44.1	85.1	2,412,314.33	Georgia
Idaho	1,201.2	1,410,598.96	849,698.85	86.3	26.1	112.4	1,582,028.76	922,000.00	97.4	40.4	137.8	682,860.89	Idaho
Illinois	2,049.2	19,080,870.63	8,521,844.65	541.0	24.5	565.5	4,806,379.95	2,185,006.77	127.3	39.2	166.5	3,560,793.36	Illinois
Indiana	1,493.6	4,841,069.81	2,325,038.73	150.9		150.9	903,188.23	375,647.33	26.2		26.2	2,098,918.42	Indiana
Iowa	2,968.4	7,461,183.62	3,175,262.01	66.0	190.2	256.2	808,633.66	338,067.84	11.9	15.1	27.0	5,310.32	Iowa
Kansas	2,844.9	5,462,334.35	2,616,606.61	256.9	27.8	284.7	862,946.78	435,946.80	33.4	90.4	123.8	1,934,282.56	Kansas
Kentucky	1,521.6	3,860,648.93	1,695,449.74	135.6	5.5	141.1	4,862,314.99	2,213,273.11	45.8	228.0	273.8	115,708.00	Kentucky
Louisiana	1,349.4	5,068,523.06	2,466,932.87	153.8	17.4	171.2	1,583,048.39	773,792.08	49.0	8.3	57.3	1,222,014.68	Louisiana
Maine	535.1	3,012,394.14	1,089,082.97	71.7	1.5	73.2	550,143.96	226,444.75	18.8		18.8	1,206,422.28	Maine
Maryland	630.7	2,060,152.03	989,662.14	52.4	12.6	65.0	646,938.32	288,773.00	8.4	5.8	14.2	5,643.03	Maryland
Massachusetts	664.0	6,541,642.10	1,743,365.72	70.7	2.6	73.3	631,733.63	167,606.00	10.5		10.5	1,788,720.32	Massachusetts
Michigan	1,624.6	9,322,319.80	3,942,567.96	212.1	30.5	242.6	521,780.27	242,475.00	25.7		25.7	2,789,104.43	Michigan
Minnesota	3,918.6	11,498,661.62	4,092,278.31	240.6	256.0	496.6	525,692.49	218,675.40	11.1	14.8	25.9	46,352.03	Minnesota
Mississippi	1,820.7	1,796,493.20	891,571.41	55.0	7.7	62.7	40,111.51	20,055.75	.1		.1	3,532,317.46	Mississippi
Missouri	2,500.6	6,340,247.74	2,615,536.03	139.8	55.5	195.3	2,640,363.32	909,414.31	39.9	27.7	67.6	701,743.96	Missouri
Montana	1,735.3	7,725,089.44	4,358,263.83	535.8	53.5	589.3	1,460,794.69	807,560.17	137.2	30.8	168.0	3,004,098.65	Montana
Nebraska	3,718.0	6,828,416.54	3,139,559.32	243.4	129.6	373.0	1,270,897.18	510,753.29	51.7	83.0	134.7	2,180,257.26	Nebraska
Nevada	1,179.3	949,063.54	840,337.62		182.0	182.0	186,710.29	165,628.15		35.1	35.1	723,022.82	Nevada
New Hampshire	352.7	1,586,108.43	573,694.89	37.3		37.3	346,913.98	106,005.00	5.4	1.6	7.0	93,767.59	New Hampshire
New Jersey	516.3	5,536,034.80	1,349,431.32	58.2		58.2						977,248.78	New Jersey
New Mexico	1,923.3	3,701,393.91	2,521,487.98	191.5	50.7	242.2	741,524.24	525,087.05	26.4	8.2	34.6	606,148.35	New Mexico
New York	2,491.0	23,966,167.76	4,780,466.00	319.1		319.1	9,577,950.00	1,743,722.50	116.6		116.6	6,542,097.86	New York
North Carolina	1,782.3	4,186,216.02	2,070,849.82	168.9	28.9	197.8	1,287,723.62	622,159.25	52.5	1.9	54.4	1,902,915.11	North Carolina
North Dakota	4,250.8	2,284,275.80	1,203,167.63	354.7	157.8	512.5	1,350,377.84	674,894.93	158.9	204.2	363.1	1,180,507.18	North Dakota
Ohio	2,215.5	20,761,861.68	6,877,869.30	387.5	29.6	417.1	5,465,862.46	1,881,314.30	69.9	18.0	87.9	91,459.09	Ohio
Oklahoma	1,895.8	4,792,879.33	2,200,512.88	146.6	61.5	208.1	2,016,660.15	943,834.11	51.4	39.2	90.6	131,500.73	Oklahoma
Oregon	1,138.6	6,011,274.27	3,618,305.10	226.0	97.3	323.3	611,974.55	366,669.70	55.6		55.6	25,209.58	Oregon
Pennsylvania	2,354.1	20,108,082.80	5,482,571.93	259.7	14.1	273.8	4,695,624.96	1,284,497.50	53.2		53.2	684,027.89	Pennsylvania
Rhode Island	196.2	1,506,856.94	586,064.33	21.7		21.7	520,359.91	148,125.00	5.9		5.9	333,199.35	Rhode Island
South Carolina	1,868.5	4,726,336.40	2,017,574.94	104.2	80.4	184.6	1,232,521.06	439,064.20	21.3	26.2	47.5	99,219.24	South Carolina
South Dakota	3,551.1	3,838,732.11	2,038,792.10	370.6	123.6	494.2	880,327.51	409,524.28	49.8	81.4	131.2	1,004,479.15	South Dakota
Tennessee	1,244.8	4,186,340.75	1,753,182.71	145.1	40.0	185.1	2,240,583.36	1,071,006.35	88.8	10.7	99.5	1,206,111.81	Tennessee
Texas	6,844.2	12,650,[illegible]9.56	5,207,080.58	396.7	138.8	535.5	3,041,145.30	1,227,904.32	63.3	92.6	155.9	4,176,175.63	Texas
Utah	968.2	1,275,141.24	887,151.64	78.7	32.2	110.9	356,570.00	259,783.40	16.1	57.5	73.6	706,519.01	Utah
Vermont	255.6	2,153,795.06	778,211.81	42.4	2.6	45.0	316,892.82	45,829.37	5.7		5.7		Vermont
Virginia	1,472.5	4,807,646.48	2,256,206.29	216.8	13.6	230.4	538,272.40	249,143.54	20.2	3.0	23.2	573,299.83	Virginia
Washington	903.2	4,040,280.89	1,751,900.00	93.6	36.3	129.9	182,586.98	83,000.00	1.7		1.7	1,199,863.86	Washington
West Virginia	700.2	3,744,304.92	1,380,940.60	80.6	37.8	118.4	1,373,872.95	480,102.90	29.8	7.1	36.9	391,874.30	West Virginia
Wisconsin	2,258.9	8,102,048.75	3,241,883.29	197.1	48.2	245.3	1,218,486.12	555,875.00	21.4	16.9	38.3	480,173.33	Wisconsin
Wyoming	1,702.8	2,084,300.10	1,357,531.50	139.3	107.8	247.1	682,129.55	490,705.72	37.0	57.4	94.4	413,707.39	Wyoming
Hawaii	41.2	853,565.90	359,459.43	21.5		21.5	226,820.16	113,414.57	9.2		9.2	1,568,624.59	Hawaii
TOTALS	84,173.7	289,465,194.65	117,844,624.42	8,054.9	2,487.6	10,542.5	71,079,362.63	28,441,064.81	1,878.9	1,334.8	3,213.7	65,256,147.78	TOTALS

[1] The term stage construction refers to additional work done on projects previously improved with Federal aid. In general, such additional work consists of the construction of a surface of higher type than was provided in the initial improvement.

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